Intensifying Beef Production on Utah Private Land: Productivity, Profitability, and Risk

D. Layne Coppock,[1] Donald L. Snyder,[2] Louise D. Sainsbury,[3] Mansi Amin,[4] and Travis D. McNiven[5]

Authors are [1]Associate Professor, Environment & Society Department, Utah State University, Logan, UT 84322-5215, USA; [2]Professor, Applied Economics Department, Utah State University, Logan, UT 84322-3530, USA; [3]Former graduate research assistant, Rangeland Resources Department, Utah State University, Logan, UT 84322, USA; [4]Former research assistant, Utah Agricultural Experiment Station, Utah State University, Logan, UT 84322-4810, USA; and [5]Former graduate research assistant, Economics Department, Utah State University, Logan, UT 84322, USA.

Abstract

It is hypothesized that Utah beef producers in certain locations could intensify private land use via improved forages and irrigation. Although intensification could increase ranch productivity and help compensate for any future restrictions in public grazing, is the approach profitable and sustainable in a dynamic environment? We investigated the efficacy of intensification using linear programming for three size-classes of model ranches. Model solutions maximize returns net of forage costs; outputs include brood-herd dynamics, optimal forage mixes, and net returns. The model is driven by 11-year risk scenarios combining high or low precipitation with high or low beef prices. We then consider current or no access to public grazing—a policy uncertainty. In general, results support the idea that intensification could be profitable, sustainable, and strategically useful under several sets of conditions. Modeled brood-herds expand and contract in response to precipitation. Optimal forage use is dominated by reliance on treated, improved, and irrigated forages. Critical irrigated forages include alfalfa hay and improved pasture. Profitability generally increases with operation size, but when public grazing is eliminated, herd sizes and profitability drop. Small and medium-sized operations respond to loss of public grazing by using more irrigated pasture and alfalfa hay, while larger operations use a wider variety of irrigated and nonirrigated forages. Sensitivity analysis indicates that optimal forage mixes for all operations remain stable even when input costs for fossil fuels double. Further increases in fuel costs, however, begin to reduce the contributions from irrigated pasture and alfalfa hay. Low precipitation (drought) has very large and negative effects on profitability in general. When drought combines with restricted access to public grazing, profitability of small and medium-sized operations drops further while profitability of large operations increases. Empirical research is needed to test model results and examine what the limiting assumptions reveal about real-world production constraints.

Resumen

Se cree que los productores de la carne de bovino de Utah podrían intensificar en ciertos lugares el uso de la propiedad privada mediante el mejoramiento de los forrajes con irrigación. ¿Aunque la intensificación aumentara productividad del rancho y compensara cualquier restricción futura de pastoreo en tierras públicas, es el enfoque provechoso y sostenible en un ambiente dinámico? Investigamos la eficacia de la intensificación usando programación linear para tres distintas extensiones de ranchos. Las soluciones del modelo maximizan la ganancia neta de los costos del forraje, los factores externos incluyen las dinámicas del hato-cría, la óptima mezcla de forrajes y las ganancias netas. El modelo se desarrolla en base a las perspectivas de riesgo de 11 años que combinan la precipitación alta o baja en combinación con precios altos o bajos del ganado. Además se tomó en cuenta el acceso o falta de éste al pastoreo en tierras públicas -como una política de incertidumbre. En general los resultados apoyan la idea que la intensificación podría ser lucrativa, sustentable y vitalmente útil bajo ciertas condiciones. Los modelos de los hatos se expanden y se contraen en respuesta a la precipitación. El uso óptimo del forraje está sujeto a la dependencia en forrajes tratados, mejorados o con el uso de irrigación. Los forrajes críticos irrigados incluyen heno de alfalfa y praderas mejoradas. Los beneficios generalmente se incrementan con el tamaño de la operación, pero cuando se elimina el pastoreo de tierras públicas tanto las ganancias como el tamaño del hato disminuyen. Las operaciones pequeñas y medianas responden a las pérdidas del pastoreo en tierras públicas utilizando más praderas irrigadas y heno de alfalfa, mientras que las operaciones grandes utilizan una variedad más amplia de forrajes irrigados y no irrigados. Los análisis de la sensibilidad indican que las mezclas óptimas de forrajes para todas las operaciones permanecen estables aun cuando la contribución de los costos de los combustibles aumente al doble. Aumentos posteriores en los combustibles, sin embargo, reducen las contribuciones de las praderas irrigadas y heno de alfalfa. La baja precipitación (sequía) tiene efectos negativos muy grandes en las ganancias en general. Cuando la sequía se combina con el acceso restringido al pastoreo en tierras públicas, los beneficios de las operaciones pequeñas y medianas se afectan aún más mientras que la ganancia en operaciones grandes es mayor. Es necesario la investigación empírica para probar los resultados de los modelos y examinar lo que revelan las a suposiciones en relación a las restricciones de la producción en el mundo real.

Key Words: drought, forage improvements, irrigated pasture, linear programming, range economics, sustainability

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Correspondence: D. Layne Coppock, Environment & Society Dept, Utah State University, Logan, UT 84322-5215, USA. Email: Layne.Coppock@usu.edu

Current addresses: Louise D. Sainsbury, US Dept of Agriculture–Natural Resources Conservation Service, 79 Winston Dr, Suite 235, Rock Springs, WY 82901, USA. Mansi Amin, 1506 Regent St, Redwood City, CA 94061, USA. Travis D. McNiven, 8106 Angel St, Sandy, UT 84070, USA.

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INTRODUCTION

Ranchers produce livestock under dynamic conditions. Risk and uncertainty due to drought, beef prices, and policy can affect operational performance (Holechek et al. 1994; Thurow and Taylor 1999). Ideally, technology and management practices should promote profitability as well as help producers better manage risk and uncertainty.

Beef production strategies vary in the degree of management inputs. For Utah ranchers, operators who employ higher-input production options tend to be in a small minority. The majority pursue lower-input, risk-averse tactics consistent with having smaller incomes and more diversified livelihoods (Peterson and Coppock 2001). We hypothesized that beef producers in more mesic places of Utah could intensify private land use via improved, irrigated pasture and grazing rotations. Such an approach potentially could have impacts on ranch productivity and profitability and help ranchers adjust to future restrictions in their access to public grazing. Focusing more livestock production on well-managed irrigated parcels could also enhance prospects for conserving fragile sites elsewhere. An important question, however, is whether such intensification is wise given risks of drought and low beef prices, and uncertainty due to policy, that are inherent to rangeland production systems.

Although relevant pasture research in Utah is limited, studies elsewhere document varied impacts of forage improvements on the productivity and profitability of beef cattle under nonirrigated and irrigated pasture conditions (Burton et al. 1994; Kouka et al. 1994; Fales et al. 1995; Phillips and Coleman 1995). Conversely, productivity of beef cattle under short-duration, rotational grazing systems on nonirrigated range is generally considered unsustainable (Hart et al. 1988; Heitschmidt et al. 1990). There is a large volume of research on public land grazing, much of which focuses on the value of public and private forage (Torell et al. 1986; Fowler et al. 1994; Van Tassell et al. 1997; Bartlett et al. 2002). Torell et al. (2002) analyze potential ranch-level impacts from altered livestock access to public lands.

We examined several aspects of the ‘‘intensification hypothesis’’ with a modeling approach using three size-classes of operations, each having varied resource endowments. We wanted to illustrate the optimal forage-investment patterns under best- and worst-case scenarios involving multiyear combinations of precipitation, beef prices, and access to public grazing. We wanted to see the extent that irrigated pasture, in particular, could emerge as a viable option. Although it may be expected that irrigated pasture could have positive implications during periods of adequate rainfall and higher cattle prices, it is possible that irrigated pasture could be unsustainable during less favorable times.

METHODS

The Setting

Beef cattle in Utah are raised by a wide variety of producers. Grazing occurs on public and private land, with the former comprising about 77% of Utah's total area (Anderson 1989). Private land is typically located in more mesic environments having higher grazing potential. Ranchers often combine cattle production with alfalfa and grain cultivation (Godfrey 1992). Ranching is a vital part of Utah's rural economy. Over 8 000 cow–calf operations contributed $475 million to the state economy in 2005 (Utah Agricultural Statistics and Utah Department of Agriculture and Food [UAS and UDAF] 2006).

About half of Utah beef producers in the late 1990s were wholly dependent on private lands for grazing, while the rest relied on both private and public resources (Peterson and Coppock 2001). A minority of Utah producers (8%) can be regarded as ‘‘active adopters'' of new technology and management practices, and when compared to the majority they tend to be wealthier, more business-oriented, and more likely to be grazing permittees (Peterson and Coppock 2001). Some of these active adopters can also be categorized as ‘‘intensifiers,'' namely, those motivated to increase productivity via private investments in forage and irrigation technology.

We used data from 25 self-declared intensifiers to support this analysis. They were sorted into three size-classes of operations based on total private acreage held. Their resource information was used to parameterize the linear programming model described below.

Empirical Model

Research was designed to assess returns from various forage improvements under changing conditions of precipitation, beef prices, and access to public grazing. From the ranch perspective, the empirical question is a dynamic constrained maximization problem. The objective is selecting a forage mix that maximizes present value of returns net of forage costs derived from beef and forage production and sales, subject to resource constraints. The model is quantified by LINDO (Linear INteractive Discrete Optimizer; LINDO Systems 1998). Model code may be obtained from the authors. Table A1 in the Appendix includes the variables used in the model, and the equations used. Equations are referenced in the text by means of numbers in square brackets that refer to the Appendix.

Linear programming models have limiting assumptions. In addition, other constraints were imposed on the model in an attempt to answer certain questions related to forage use including the following: 1) ranch operators will attempt to maximize returns net of feed costs (net revenue [NR]) subject to their production function, resources, and biological constraints; 2) weather cycles are predictable and known; 3) forage produced in a year is consumed in that year; 4) irrigation water is sufficient to support crops and pasture except during consecutive drought years (defined below); 5) a 15% growth/liquidation rate is imposed on the base herd from year to year (J. P. Workman, personal communication, 1999); 6) nonuse of public grazing permits is limited to one year out of every three; 7) capital investment (i.e., cash flow necessary to finance herd growth) and labor are available as needed and, therefore, not considered constraints; and 8) all herd replacements for maintenance or growth were assumed to come from within the herd. Others have correctly identified a cash flow constraint as a limiting factor (Tanaka et al. 2007), but our interest lies in forage use and herd dynamics in an unconstrained environment.

Objective Function. The ranch operator is assumed to maximize the present value (PV) of revenues net of feed costs

Table 1. Private land (hectares) and initial livestock parameter values for Utah beef operations.[1]

Production attribute	Operation size		
	Small	Medium	Large
Land			
Wet meadow	6.9	17.8	87.0
Irrigated cropland/pasture	54.2	113.7	130.7
Nonirrigated cropland	6.1	20.2	0.0
Nonirrigated grazing land	55.9	298.3	1 102.0
Upper foothill range	38.9	208.0	768.9
Lower foothill range	16.2	85.4	315.3
Desert range	0.8	4.9	17.8
Total	123.1	450.0	1 319.7
Livestock			
Brood-herd size (hd)	65	308	286
Cows replaced ($hd \cdot yr^{-1}$)	10	46	43
Calves born ($hd \cdot yr^{-1}$)	58	276	256
Bulls	3	15	14
Horses	2	6	5

[1]Profiles on irrigated versus nonirrigated grazing lands are based on a sample of 25 operators who were planning to intensify use of private land (Peterson and Coppock 2001; Sainsbury 2001). Breakout of nonirrigated land follows Evans (1992). See Tables 2 and A2 for descriptions of site types. Annual replacement rate for cows is 15%, annual calving rate is 90%, cow:bull ratio is 20:1, and cow:horse ratio is 50:1.

(NR), where PV is calculated using discount rates of 4% and 8% over 11 yr. Revenues result from sales of calves, yearlings, cull bulls, cull cows, surplus hay (improved and unimproved), and barley [1]. Variable costs are limited to those required to produce forage because we are interested in the impact various forage treatments could have on net returns, and it can reasonably be assumed that nonforage costs would be similar regardless of forages adopted [1].

Initial Conditions. Deeded land resources used for the model are shown in Table 1. Small operations have an even split between irrigated and nonirrigated lands, while large operations have almost fivefold more nonirrigated land than irrigated land. Overall, large operations averaged 3–10 times more private land compared to medium-sized or small operations, respectively. Seasonal public grazing permits augment private land. Animal unit months (AUMs) for model operations are allocated as 28%, 39%, 9%, and 24% of total demand for spring, summer, fall, and winter, respectively, based on aggregate survey data. Total annual permitted AUMs ranged from 453 (small operations) to 1 003 (medium) and 1 574 (large). Each modeled operation is assumed to use public permits at least two out of every three years to avoid more than one year of nonuse. Livestock parameter values corresponding to operation size are also shown in Table 1; beginning cow-herd size is set for the first year of the model consistent with these data. No long yearling steers or heifers are assumed available for sale in the first year.

Productivity and costs associated with 13 grazed and cultivated sites are shown in Table 2. Treatments represent various combinations of improved plant materials, vegetation manipulations, inputs of water, fertilizer, and herbicides, and implementation of grazing management schemes. The treatment package varies widely by site type; this is summarized in Table A2 in the Appendix. Untreated cases for grazing are typified by native forages, with sites often in poor to moderate condition. Treated cases are derived from expert opinion in terms of "realistic and conservative" levels of inputs necessary to maintain suitable production levels. Five grazing sites are nonirrigated, while four are either naturally subirrigated or surface irrigated via human intervention. Irrigation and treatment application result in dramatic increases in forage productivity and potential stocking rate for grazing sites. Treatment results in forage productivity increases that vary from 28% (wet meadow) to almost 10-fold (irrigated pasture). Treatments result in costs per hectare that increase from 31% (lower foothill range) to nearly 700% (irrigated pasture). Conversely, treatment results in markedly lower costs per AUM in all grazing sites except wet meadow, primarily because of the high level of productivity on treated lands (Table 2).

We wanted to drive the model using a combination of favorable or unfavorable commodity prices with favorable or unfavorable precipitation scenarios. We use an 11-yr time frame (22 yr total; UAS and UDAF 1978–1999) for constructing scenarios reflective of the beef price cycle (Stockton and Van Tassell 2007). Prices peak at around US\$1.87–2.09 $\cdot$ kg^{-1} for heifer and steer calves, respectively, which averages about 64% higher than the lowest prices of \$1.10 $\cdot$ kg^{-1} and \$1.32 $\cdot$ kg^{-1}. Prices for all classes of cattle were based on historical price differences between feeder steers and each class of cattle (UAS and UDAF 1978–1999). For example, if feeder heifer prices were historically \$8 $\cdot$ cwt^{-1} (\$8 per 100 pounds) lower than feeder steer prices, the heifer price in any given year was the feeder steer price adjusted downward by that amount over the two 11-yr periods. Similar adjustments were made to all other beef prices.

We selected two highly contrasting 11-yr sequences of precipitation based on the Palmer Drought Severity Index (PDSI) for northern Utah during 1895–1999 (Sainsbury 2001). The wettest and driest sequences occurred during 1906–1916 and 1952–1962, respectively, the former having more variable yearly precipitation. Hay and barley prices are derived from recent data (UAS and UDAF 1978–1999). All forage productivities reflect drought-year effects, as will be shown.

Equations of Motion. Equations of motion are necessary to model specific ranch functions and reflect how the system state changes over time. The ranch model includes equations of motion that describe how changes in the herd are dependent on time, the herd variables themselves, and management decisions regarding the herd in relation to the price and precipitation patterns. The seasons are blocked into four three-month segments (December to February, March to May, etc.).

Ranch operation equations of motion. Cow numbers are allowed to increase or decrease by up to 15% annually following the first year [2, 3] (J. Workman, personal communication, 1999). The AUMs required by season [4] are based on the number of animals raised by type. Cow-to-bull and cow-to-horse ratios are also included as constraints [5 and 6, respectively] to better account for forage consumed. Cow-to-cull cow [7] and bull-to-cull bull [8] ratio constraints are added to reflect proper herd turnover. A calving percentage of 90% is assumed, with equal numbers of steers and heifers born [9, 10, 11]. Replacement heifers are assumed to come from the 45 heifer calves born each year for each 100 cows in the herd [11].

Table 2. Productivity and costs for maintaining or improving forage types for Utah beef operations.[1]

Forage type	Forage productivity		Stocking rate		Costs	
	$AUMs \cdot ha^{-1}$	$kg\ DM \cdot ha^{-1}$	$ha \cdot hd^{-1}$	Months	$\$ \cdot ha^{-1}$	$\$ \cdot AUM^{-1}$
Grazing sites						
Untreated desert range	0.30	81	13.48	4	4.50	15.20
Untreated upper foothill range	0.49	135	10.12	5	25.32	51.25
Treated upper foothill range	2.47	674	2.02	5	41.74	16.90
Untreated lower foothill range	1.23	337	4.05	5	25.32	20.50
Treated lower foothill range	2.47	674	2.02	5	33.10	13.40
Untreated wet meadow	10.50	2 863	0.57	6	35.82	3.41
Treated wet meadow	13.49	3 678	0.44	6	78.18	5.70
Untreated irrigated pasture	3.11	849	1.30	4	71.88	23.28
Treated irrigated pasture	30.63	8 353	0.20	6	484.49	15.82
Cultivated sites						
Untreated alfalfa	22.48	6 130			672.14	29.90
Treated alfalfa	44.95	12 260			798.67	17.77
Aftermath	2.47	674			37.54	15.20
Barley	16.55	4 513			680.81	41.14

[1]Productivity of forage sites is based on expert opinions (H. Horton, personal communication, September 2004; R. Banner, personal communication, December 2006). Production costs have been derived as follows: alfalfa hay (Utah Agricultural Statistics and Utah Department of Agriculture and Food [UAS and UDAF] 1998; barley (UAS and UDAF 2002); treated pasture (UAS and UDAF 1995); untreated pasture (UAS and UDAF 1993); wet meadow (UAS and UDAF 1993); lower foothill, upper foothill, and desert range (Sainsbury 2001); public permits (http://www.blm.gov/nhp/news/releases/2005). Budgets for the "treated" options were primarily drawn from those published by UDAF, but that were developed under the direction of, or in cooperation with, E. Bruce Godfrey, Economist in the Department of Applied Economics at Utah State University. Given the variety of "useful lives" for various treatment options, the treatments are actually amortized within the respective crop budgets following generally accepted budgeting procedures. For instance, the establishment costs of treated alfalfa hay were amortized over a useful life of 6 yr, treated pasture establishment costs over a useful life of 10 yr, but machinery costs included within the budgets were amortized over their respective useful lives (e.g., 15 yr for tractors and ground-working implements, 20 yr or more for buildings, but only 3–5 yr for small equipment items such as hand tools.) Unfortunately, space does not allow a detailed reproduction of each budget, and even if it did, it would not contain all of the information associated with the amortization of various machinery, building, or equipment components. For the untreated nonirrigated forages, costs were based on those suggested by various experts. Yields were also based on expert opinions and reflect the most current varieties available under the treated options rather than those associated with historical production levels. One animal unit month (AUM) is the forage required to support one 454-kg brood cow per month and equates to 273 kg dry matter (DM). This value considers daily DM intake to be 2% of live weight and reflects an average for a wide variety of forage-quality conditions (Holechek et al. 2001). The month column indicates number of months a forage type is used in a given year. See Table A2 for forage-type descriptions. hd indicates brood-herd size.

Steers and heifer sale weights are assumed to increase by 0.90 $kg \cdot yr^{-1}$ to reflect herd quality improvements.

Forage equations of motion. Total AUMs available are estimated for each type of forage and summed [12] based on specific forage productivities. Irrigated cropland is constrained in total and by type [13–18]. Public permits are limited, as previously noted, to allow periodic nonuse [19]. Long yearlings available for sale are constrained by the number of previous year's calves [20, 21].

Accounting Equations. Annual NR is generated for calculation of the PV for each scenario [22]. Aftermath availability is limited to total hay production acreage [23]. A crop rotation constraint is added to ensure that alfalfa was properly rotated with grain [24]. AUMs per season are calculated and summed across all selected forages [25]. Accounting equations are needed to sum animal [4] and forage [25] AUM numbers, set them equal to each other, and allow annual changes. Constraints are added to restrict feed availabilities during certain seasons [26–30]. Total labor required over the 11 yr is totaled [31].

Ranch Operation Boundary Conditions. A restriction is imposed so that the ranch has to either produce or purchase sufficient forage to feed the herd throughout the year [1], while allowing for changes in herd size from year to year. Cow/calf pairs are assumed equivalent to one AUM, horses at 1.5 $AUMs \cdot head^{-1}$, bulls at 1.2 $AUMs \cdot head^{-1}$, and yearling steers and heifers at 0.67 $AUMs \cdot head^{-1}$ [5]. Precipitation influences forage production from rain fed forages and, to a lesser extent, irrigated crops. For example, on nonirrigated grazing land a slightly, moderately, or extremely dry year based on PDSI values reduces forage production by 25%, 50%, and 80% of average, respectively. Moderately or extremely wet years are assumed to increase forage production by 108–117%. Annual precipitation can also affect irrigation. During one extremely dry year or consecutive moderately dry years, irrigated forage production is reduced by 50% (Sainsbury 2001).

Equations allow the model to choose between treatment or nontreatment of various base forages to produce the highest (optimal) NR from those resources. The 24 cases included various combinations of precipitation, beef prices, and access to public grazing.

RESULTS

Public Grazing Permits Maintained

Brood Herd Dynamics. Averaged for all scenarios, brood-herd numbers change across the 11 yr from 65 to 89 head (small operation), 308 to 229 head (medium), and 286 to 328 head (large; Table 3). Higher precipitation allows herds to expand and peak by year 9. In contrast, lower precipitation reduces base herd size. Beef prices have only minor influences on herd dynamics.

Table 3. Brood-herd numbers over an 11-yr modeling sequence for Utah beef operations.[1]

	Small						Medium						Large					
	Precip.		Price		Precip., Price		Precip.		Price		Precip., Price		Precip.		Price		Precip., Price	
Year	H	L	H	L	HH	LL	H	L	H	L	HH	LL	H	L	H	L	HH	LL
Start	65	65	65	65	65	65	308	308	308	308	308	308	286	286	286	286	286	286
Peak/trough	170	30	98	101	167	31	417	116	293	240	470	116	598	149	401	345	645	140
End	150	38	83	104	127	36	332	136	218	250	300	136	487	190	305	371	424	193

[1]Access to public grazing is maintained. See text for descriptions of small, medium, and large operations, higher (H) or lower (L) precipitation scenarios, and higher (H) or lower (L) scenarios for beef prices. The best-case scenario consists of higher beef prices and higher precipitation combined (HH). The worst-case scenario consists of lower beef prices and lower precipitation combined (LL). Brood herds gradually expanded and peaked by years 7–9 primarily in response to higher precipitation. Subsequent declines in herd numbers are attributable to the occurrence of drier years and/or reduced cattle prices.

Patterns of Optimal Forage Use. Table 4 summarizes effects of precipitation and beef price scenarios on forage use, with two patterns evident. First, with the exception of upper foothill range, forage use is dominated by reliance on treated compared to untreated options. This particularly occurs for alfalfa hay, irrigated pasture, and lower foothill range. It also often occurs for wet meadow, except for large operations where use of treated and untreated options becomes co-dominant during drier scenarios. Second, use of surface-irrigated forages is dominant over use of nonirrigated or subirrigated forages. Averaged across all operations, use of surface-irrigated forages is 58% of AUMs versus 30% and 12% for non- or subirrigated forages, respectively. Operation size influences forage use. Small operations rely on surface-irrigated forage for 61% of their AUMs, with non- or subirrigated forages supplying 31% and 8%, respectively. In contrast, medium-sized operations rely more on surface-irrigated forage (71% of AUMs), less on nonirrigated forage (18%), and a similar level of subirrigated forage (11%). Large operations use less surface-irrigated forage (44% of AUMs) compared to that for small or medium operations. Consequently large operations use relatively more nonirrigated (34%) and subirrigated (21%) forage. Forage use was influenced by the endowment of ranch resources. All operations have a core of irrigated land, but as operation size increases, the proportion of nonirrigated land increases (Table 1).

Isolated effects of precipitation and price. Effects of precipitation on forage use are to the left in Table 4. Compared to patterns for the drier scenarios, the wetter scenarios for all operations result in 1) a markedly higher reliance on home-grown, treated hay as well as treated pasture, 2) a markedly lower reliance on purchased hay and crop residues, and 3) a slightly lower reliance on treated wet meadow. Use of foothill range, or untreated surface-irrigated resources, is low in most cases regardless of precipitation scenario. Use of public grazing dominates use of nonirrigated forage for all operations. Drier scenarios reduce average annual AUMs by 54%, 39%, and 47% for small, medium, and large operations, respectively, as compared to that for wetter scenarios.

Effects of beef price on forage use are to the right in Table 4. Compared to the patterns for lower price scenarios, the higher price scenarios resulted in only minor shifts in forage resource use with small discrepancies due to operation size. Treated, irrigated resources—and public grazing—again dominate. The higher-price scenarios show an increase in average annual AUMs by only 3–5% across all operations compared to that for lower-price scenarios.

Joint effects of precipitation and price. Effects of a best-case scenario (wetter and higher prices) versus a worst-case scenario (drier and lower prices) on forage use with public grazing maintained are shown in Table 5. Patterns again illustrate dominant influences of precipitation. Compared to the worst case, the best case typically results in 1) a markedly higher reliance on home-grown, treated hay as well as treated pasture, and 2) a markedly lower reliance on purchased hay and crop residues. There is also a lower reliance on treated wet meadow during the best-case scenarios for small and medium-sized operations, but use of treated wet meadow is more similar under both extremes for large operations. Use of foothill range, or untreated surface-irrigated resources, is again typically low regardless of precipitation. Use of untreated wet meadow, however, spikes for large operations in the worst-case scenario. Public grazing dominates use of nonirrigated forage for all operations and tends to increase under the worst case for large—but especially for small—operations. Reliance on public grazing appears to remain steady for medium-sized operations in both best- and worst-case situations (Table 5). The worst-case scenario reduces average annual AUMs by 56%, 41%, and 50% for small, medium, and large operations, respectively, compared to that for best-case scenarios. This is only slightly more than that observed for isolated effects of precipitation (Table 4).

Public Grazing Permits Eliminated

When public grazing access is cut off, brood-herd dynamics are similar to those shown in Table 3, but herd sizes are slightly reduced (McNiven 2006). The reduction varies from 6% (medium and large operations) to 10% (small operations).

Effects of change in public-grazing access on forage use patterns are shown in Table 6. The medium-sized operation is relatively less reliant on public grazing than the small or large operation. The medium operation is consequently most reliant on treated hay, purchased hay, and treated pasture. Small operations rely most heavily on crop residues, while large operations rely more on nonirrigated or subirrigated grazing.

Compared to situations where public grazing access is maintained, the elimination of permits—in general—results in a higher reliance on treated, surface-irrigated resources across all operations, a marked increase in use of treated wet meadow by large operations, and—as operation size increases—a

Table 4. Effects of precipitation and beef price scenario (higher, lower) on percentage use of forage supplies over an 11-yr modeling sequence for Utah beef operations.[1]

	Precipitation						Beef price					
	Small		Medium		Large		Small		Medium		Large	
Forage category	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower	Higher	Lower
Treated hay	38.1	8.6	44.6	15.7	28.2	8.6	25.1	28.9	34.9	28.8	20.6	18.8
Untreated hay	0.9	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
Purchased hay	0.0	20.5	0.0	33.2	0.0	16.1	8.4	5.7	13.5	13.9	6.4	5.5
Treated pasture	20.1	6.8	20.9	13.4	12.4	5.9	17.7	12.4	15.3	20.4	9.5	10.7
Untreated pasture	4.2	5.2	0.8	1.6	2.3	2.6	4.3	4.8	1.1	1.2	2.2	2.5
Aftermath	2.3	10.9	2.5	5.5	1.6	5.8	5.3	5.6	4.1	3.7	3.3	3.2
Barley	0.0	4.1	0.0	2.1	0.0	2.3	1.4	1.3	0.9	0.9	0.8	0.9
Treated lower foothill range	2.0	1.3	3.7	2.3	9.5	4.6	1.7	1.8	3.0	3.2	7.9	7.2
Untreated lower foothill range	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Treated upper foothill range	1.1	1.5	3.9	1.1	3.5	0.0	0.8	1.4	2.6	2.3	1.6	1.7
Untreated upper foothill range	1.1	1.1	1.5	1.4	5.4	4.2	1.0	1.0	1.3	1.6	4.8	4.9
Treated wet meadow	5.8	9.7	4.7	6.6	12.2	14.0	7.5	7.7	5.8	6.0	15.1	12.5
Untreated wet meadow	0.0	0.8	0.0	0.0	4.7	11.8	0.3	0.3	0.0	0.0	6.2	9.3
Desert range	0.0	0.0	0.0	0.0	0.1	0.1	T[2]	T[2]	T[2]	T[2]	0.1	0.1
Public grazing permits	24.4	29.6	17.4	16.8	20.2	24.1	26.4	27.9	17.4	18.0	21.4	22.8
Average annual AUMs	1 605	745	5 090	3 122	6 426	3 363	1 100	1 064	3 846	3 736	4 649	4 441
SE annual AUMs	165.8	52.1	173.1	325.8	510.1	227.9	64.4	81.1	188.1	244.7	262.3	265.0

[1]Access to public grazing is maintained. See text for descriptions of small, medium, and large operations, higher or lower precipitation scenarios, and higher or lower scenarios for beef prices. Forage types are described in Tables 2 and A2. One animal unit month (AUM) equals 273 kg dry matter (Holechek et al. 2001). The SE for AUMs is calculated over 11 yr of the model runs and illustrates interannual variability. The SE values vary from 3% to 10% of average annual AUMs.

[2]T denotes trace amount.

steadily increasing use of treated and untreated rain-fed forage (Table 6). All modeled operations are largely able to adjust to loss of public permits in terms of average annual AUMs. For small operations, loss of public permits (27% of AUMs) is made up through greater use of treated pasture (by almost 15 percentage points or a 113% relative increase), purchased hay (by 5 percentage points; 48%), and home-grown, treated hay (by 6 percentage points; 27%). Net change in use of all other forages combined is small (by slightly more than 1 percentage point, or a 3% decline). Increases occur, however, in use of crop residues, treated foothill range, and treated wet meadow by small operations with public permits eliminated; collectively these add to slightly over 2 percentage points, an 11% increase. For medium-sized operations, loss of public permits (17% of AUMs) is made up through greater use of home-grown, treated hay (by 8 percentage points; a 26% relative increase), treated irrigated pasture (by over 4 percentage points; 26%), and purchased hay (by 3 percentage points; 18%). Net change in use of all other forages combined was small (by less than 1 percentage point, or a 3% decline). Increases were observed, however, in the use of aftermath, treated foothill range, and treated wet meadow by medium-sized operations with public permits eliminated; collectively these added to almost 3 percentage points, or a 20% increase. For large operations, loss of public permits (22% of AUMs) was made up via greater use of treated irrigated pasture (by almost 6 percentage points or a 63% relative increase), treated wet meadow (by over 7 percentage points; 55%), home-grown, treated hay (by 5 percentage points; 28%), and purchased hay (by 1.3 percentage points, 16%). Net change in use of all other forages combined was about 3 percentage points or a 10% increase. Increases were observed in the use of crop residues as well as treated and untreated foothill range; collectively these add to over 7 percentage points or a 41% increase. In several cases use of some forage options consistently declined when public permits were cut. These included use of untreated irrigated pasture and untreated wet meadow (Table 6).

Profitability of forage investments for operations under two discount rates and eight production scenarios is illustrated in Table 7. Results indicate that PV values are positive and steadily increase with operation size when precipitation is higher—regardless of access to public grazing—although eliminating public grazing reduces PV for the small and medium operations with less of a decline for the large operation. These effects of eliminating public grazing on profitability appear modest, however, compared to those due to drought. Average declines in PV due to lower precipitation range from −184%, −158%, and −105% for medium, small, and large operations, respectively, as considered here for the 8% discount rate for illustrative purposes.

The average annual value of an AUM lost due to restricted access to public grazing varies from \$0.50 to \$2 for small and medium-sized operations, respectively, depending on drought and price conditions. However, for the large ranch operation, the loss in average per-AUM value ranges from \$2 to over \$4 under the high precipitation scenarios to a gain in average per-AUM of \$3.50 to \$5.45 under the low precipitation scenarios, indicating that a loss of public AUMs is generally beneficial to the large ranches when drought conditions prevail. So except for the large ranches under drought conditions, these values are similar to the \$3 $\cdot$ AUM^{-1} to \$10 $\cdot$ AUM^{-1} given by Torell et al. (2002) for ranches in Idaho, Nevada, and Oregon.

Table 5. Effects of best- and worst-case scenarios for precipitation combined with beef prices on percentage use of forage supplies over an 11-yr modeling sequence for Utah beef operations.[1]

	Small		Medium		Large	
Forage category	HH	LL	HH	LL	HH	LL
Treated hay	36.3	9.2	50.4	16.7	30.2	8.7
Untreated hay	0.0	0.0	0.0	0.0	0.0	0.0
Purchased hay	0.0	17.1	0.0	33.0	0.0	15.0
Treated pasture	24.9	7.1	16.2	12.8	12.1	6.8
Untreated pasture	3.9	5.6	0.7	1.7	2.1	2.7
Crop aftermath	2.2	11.3	2.8	5.4	1.7	5.9
Barley	0.0	4.1	0.0	2.1	0.0	2.4
Treated crested wheatgrass	2.0	1.3	3.6	2.4	9.7	3.8
Untreated crested wheatgrass	0.0	0.0	0.0	0.0	0.0	0.0
Treated native foothill range	0.0	0.9	3.8	1.1	3.2	0.0
Untreated native foothill range	1.1	1.2	1.2	1.4	5.0	3.9
Treated wet meadow	5.8	10.3	4.6	6.6	12.1	10.7
Untreated wet meadow	0.0	0.8	0.0	0.0	4.5	15.5
Desert range	T[2]	T[2]	T[2]	T[2]	0.1	0.1
Public grazing permits	23.9	31.2	16.9	16.8	19.4	24.7
Average annual AUMs	1 614	706	5 261	3 147	6 557	3 256
SE annual AUMs	174.6	73.5	289.9	354.9	609.3	297.1

[1]Access to public grazing is maintained. See text for descriptions of small, medium, and large operations, higher or lower precipitation scenarios, and higher or lower scenarios for beef prices. HH denotes higher precipitation combined with higher beef prices, and LL denotes lower precipitation combined with lower beef prices. Forage types are described in Tables 2 and A2. One animal unit month (AUM) equals 273 kg dry matter (Holechek et al. 2001). The SE for AUMs is calculated over 11 yr of the model runs and illustrates interannual variability. The SE values vary from 6% to 11% of average annual AUMs.

[2]T denotes trace amount.

Altered access to public grazing affects ranch profitability during drought, but the effect depends on operation size (Table 7). For small operations, public grazing access appears to have little or no influence on PV during drought. Effects become more apparent with the medium operations where reduced public access lowers profitability by 3–12%. In contrast, large operations actually improve profitability during drought by reducing their reliance on public grazing. This gain for the large ranch was realized because of elimination of the requirement that public permits be used two out of three years. If no constraints force use of public permits, the large ranch simply does not use public grazing during drought in this model.

Expanding animal numbers is not without cost. To maintain the herd growth suggested by the models for the high-price, high-precipitation scenario the minimum cost would be $600 000 for the large ranch. Such an investment would adversely affect cash flow while building overall equity. Furthermore, costs associated with herd growth are not fully offset by those years when herd numbers decline due to lower overall prices. Assuming an equal likelihood of occurrence among the four joint scenarios, this suggests a loss of over $250 000 for the large ranch. The small and medium ranches also incur major losses (Table 7).

DISCUSSION

General Findings

Despite limitations of linear programming (see Empirical Model section under Methods) this work underscores some important concepts. Results illustrate the potential utility of investing in a wide variety of forage improvements, developing some irrigated pasture, and maintaining access to a diverse forage base, both on- and off-ranch. The hypothesis that improved, irrigated pasture could have utility for production and profitability in these scenarios is supported. The utility of forage improvements in general, and that for surface irrigated options in particular, persisted despite imposition of severe drought conditions. The production circumstances and risk tolerance, however, for every real-world operation are unique. Risk-management interventions must therefore be tailored for each situation. This research yields only very general perspectives that require verification via empirical observation.

Options to rely on improved forages dominate all model solutions because improved forages have lower costs per AUM. The exception is wet meadow, where cost per treated AUM exceeds that of untreated by 67%. This is due to added expense for land preparation.

Options to rely on irrigated forage also dominate all model solutions. Given similarity among costs per treated AUM for surface-irrigated and nonirrigated sites (i.e., $13.40–17.77 per AUM) the main difference in the utility of irrigated forage is in terms of biomass yield. Biomass yield on treated, surface-irrigated sites averages 15 times higher than that of treated, nonirrigated sites. Forages prioritized for use by the model have the highest productive potential (Evans and Workman 1994).

Model operations rely on a wide diversity of forage resources. Using a 1% threshold for the cumulative, minimum contribution of total AUMs from any given forage over 11 yr, the small, medium, and large operations rely on 9, 10, and 12 forage types, respectively. The proportional breakdown of

Table 6. Effects of access to public grazing (current access or no access) on percentage use of forage supplies over an 11-yr modeling sequence for Utah beef operations.[1]

Forage category	Small		Medium		Large	
	Current access	No access	Current access	No access	Current access	No access
Treated hay	23.4	29.7	30.1	37.9	18.4	23.5
Untreated hay	0.5	0.5	0.0	0.0	0.0	0.0
Purchased hay	10.2	15.1	16.6	19.6	8.0	9.3
Treated pasture	13.4	28.6	17.2	21.6	9.2	15.0
Untreated pasture	4.7	3.4	1.2	0.5	2.4	1.9
Crop aftermath	6.6	7.0	4.0	4.4	3.7	5.6
Barley	2.0	2.2	1.1	1.1	1.1	1.2
Treated crested wheatgrass	1.6	2.2	3.0	3.6	7.1	9.7
Untreated crested wheatgrass	0.0	0.0	0.0	0.0	0.0	0.0
Treated native foothill range	1.3	1.5	2.5	4.2	1.8	4.4
Untreated native foothill range	1.1	1.1	1.5	1.2	4.8	5.1
Treated wet meadow	7.8	8.5	5.7	5.9	13.0	20.1
Untreated wet meadow	0.4	0.2	0.0	0.0	8.3	4.2
Desert range	T[2]	T[2]	T[2]	T[2]	0.0	0.0
Public grazing permits	27.1	0.0	17.2	0.0	22.2	0.0
Average annual AUMs	1 175	1 109	4 106	3 914	4 895	4 631
SE annual AUMs	93.2	83.8	213.4	190.5	321.8	292.2

[1]Access to public grazing is maintained. See text for descriptions of small, medium, and large operations. Forage types are described in Tables 2 and A2. For each column the results are averaged across the four combinations of precipitation and beef prices. It is assumed that each combination occurs at a frequency of 0.25. One animal unit month (AUM) equals 273 kg dry matter (Holechek et al. 2001). The SE for AUMs is calculated over 11 yr of model runs and illustrates interannual variability. The SE values vary from 5% to 8% of average annual AUMs. Of particular note are within size-class comparisons of average annual AUMs. Considering 2.0 $\times$ SE as a general indicator of mean separation, none of the pairs significantly differ ($P < 0.05$).

[2]T denotes trace amount.

forage use for the large operation concerning surface-irrigated, nonirrigated, and subirrigated forage is 43:36:21, respectively, with 16% of the total coming from private, unimproved sites overall. The same breakdown is 61:31:8 (with 7% unimproved) for the small operation and 70:24:6 (with 3% unimproved) for the medium operation. Increasing operation size thus has a positive influence on the diversity of forages used in this model.

Compared to variation in beef prices, variation in precipitation has much greater effects on forage use and NR. This is because extant variation in precipitation inputs is much greater than that for beef prices. In addition, the PDSI coefficients directly affect forage production.

Model Limitations and a Reality Check

At face value, model results suggest that efforts to upgrade and diversify forage resources, and boost forage productivity via irrigation systems, should be commonly observed on private lands in Utah. Although a detailed and systematic survey is lacking, it is relevant to note that a recent surge in beef cattle numbers has been documented for counties in Utah that are predominately private land, and that increased levels of irrigated pasture development have been observed in some locations (E. B. Godfrey, unpublished data, 2007; personal communication, December 2006).

Nevertheless, a major source of potential discrepancy between modeled and observed outcomes probably involves the validity of linear programming assumptions. For example, it can be debated whether ranchers are able or willing to maximize profitability of their operations. Adoption of intensive production methods may require amounts of labor and capital that are unattainable for most producers. For an example of the latter, in the best-case model scenario that combines higher beef prices and higher precipitation, the net capital investment for just expanding brood herds ranges from $29 000 to $290 000 depending on ranch size. Adding capital constraints to the model is problematic because they tend to be arbitrary. Hence, no fixed cost or living allowance was included in the modeling effort.

The model also incorporates the assumption that the 11-yr precipitation sequence is known. This, in part, may explain the rapid expansion of modeled brood herds in response to higher precipitation. Such dynamics may be quite unlike what typically occurs in Utah, however, because the statewide aggregate herd has been relatively stable for decades (UAS and UDAF 1980–2005). We speculate that ranchers may elect to maintain a conservative brood herd size to better manage ecological and economic risk, including increased capital costs.

The model assumptions include that irrigation water is sufficient, although 50% cuts in irrigation water were applied either during very dry years or after a sequence of moderately dry years. The high reliance of our modeled operations on irrigation water invites challenge. Review of records for northern Utah's Cache Valley, however, suggests that cuts in irrigation water to agricultural producers remain as rare events. Therefore, for operations located in mesic mountain valleys or adjacent to perennial rivers, our modeled water supply is likely realistic.

Table 7. Present value (PV) of gross return net of forage costs for Utah beef operations under eight combinations of precipitation, beef prices, and access to public grazing over 11 yr.[1]

Scenario	Operation size: Small	Medium	Large
8% discount rate			
Current access to public permits			
Higher precipitation, higher price	$35 810.00	$115 605.00	$440 733.00
Higher precipitation, lower price	$24 828.00	$123 230.00	$355 991.00
Lower precipitation, higher price	−$20 257.00	−$128 542.00	−$6 936.00
Lower precipitation, lower price	−$9 287.00	−$71 560.00	$36 758.00
No access to public permits			
Higher precipitation, higher price	$29 957.00	$85 493.00	$406 038.00
Higher precipitation, lower price	$20 451.00	$105 768.00	$332 072.00
Lower precipitation, higher price	−$20 355.00	−$132 301.00	$42 164.00
Lower precipitation, lower price	−$8 072.00	−$80 172.00	$67 844.00
4% discount rate			
Current access to public permits			
Higher precipitation, higher price	$48 425.00	$152 887.00	$600 538.00
Higher precipitation, lower price	$30 923.00	$145 187.00	$469 088.00
Lower precipitation, higher price	−$22 871.00	−$146 903.00	$347.00
Lower precipitation, lower price	−$12 993.00	−$95 542.00	$43 142.00
No access to public permits			
Higher precipitation, higher price	$41 036.00	$115 852.00	$551 846.00
Higher precipitation, lower price	$25 443.00	$122 809.00	$436 950.00
Lower precipitation, higher price	−$10 837.00	−$150 500.00	$66 305.00
Lower precipitation, lower price	−$22 250.00	−$104 949.00	$86 261.00

[1]See text for descriptions of small, medium, and large operations, higher or lower precipitation scenarios, higher or lower scenarios for beef prices, and for estimation of permitted AUMs. The PV values assume 4% and 8% discount rates for comparative purposes. The 8% discount rate is used to reflect a conservative, real opportunity cost of capital, whereas the 4% rate is used to reflect what some contend is a long-run social discount rate. Since we are discussing private production possibilities, the real opportunity cost of capital approach is believed to be the more accurate of the two.

Key Resources and Planning

Irrigated forages are highly valuable resources. Reliance on such key resources in model solutions varied according to best- or worst-case scenarios. For example, an "optimistic producer" operating the small model ranch and planning for a best-case scenario of higher precipitation and beef prices relies on home-grown hay and irrigated pasture for about 36% and 25%, respectively, of cumulative AUMs over 11 yr. However, a "pessimistic producer" planning for a worst-case scenario of lower precipitation and lower beef prices relies on home-grown hay and pasture for only about 9% and 7%, respectively, of cumulative AUMs. A similar pattern occurs for the large operation. Irrigated pasture and home-grown hay thus have different utilities (marginal values) depending on precipitation scenario, confirmed with sensitivity analysis (McNiven 2006). Compared to the optimist, the pessimist could plan to manage fewer acres of irrigated pasture and hay fields, arrange for future access to more purchased hay off-ranch, rely slightly more on wet meadow grazing, and maintain or increase permitted AUMs to maximize NR.

Drought Management and Public Policy

Compared to wetter scenarios, drier scenarios resulted in an overall reduction of forage production of 50%. This represents a "severe" agricultural drought (Thurow and Taylor 1999). Model results indicate that the ability to purchase hay and access public lands during dry years are important coping tactics for all operations, consistent with the idea that having access to "external" resources is important for risk management.

Drought effects on NR varied with operation size, although the effect was negative and substantial for all. The PV for investments when access to public grazing is maintained is negative for small and medium operations, with averages of −$14 772 and −$100 051, respectively, over 11 yr. For large operations, in contrast, the average PV is +$14 911. It appears, consistent with these results, that larger private land holdings allow access to more forage types under a wider variety of environmental and market conditions. It also is a function of returns to size. It should be noted that the number of AUMs provided by public lands is not reduced in the model by drought, though they most certainly would be in real-world situations.

Elimination of public grazing results in an average decline in NR of 18% for medium and small operations as well as 7% for large operations. The ability of the large ranch to more effectively mitigate loss of public grazing is probably again related to its broader base of forage production. Intensified use of private resources allows each model ranch to largely compensate for elimination of public AUMs, estimated as 17–27% of cumulative total AUMs over 11 yr. In general this supports the idea that the ability to compensate for loss of public grazing depends on the amounts and types of alternative forage resources (Torell et al. 2002). The spread in value we estimated from the loss of public AUMs was influenced by drought and operation size. The average annual loss associated with restricted access to public permits over the 11 yr was less than $1 · AUM^{-1} for small ranches and $2 · AUM^{-1} for medium ranches. However, restricted access to public permits actually improved for the large ranch by $0.51 · AUM^{-1}.

Insights From Sensitivity Analysis

We recognize that our research scenarios are not exhaustive. We have not incorporated probabilities for extended drought or higher precipitation sequences for the future given the uncertainties of climate change outcomes. Some scenarios forecast generalized xerification for the region while others suggest less snow but more growing-season precipitation (Wagner and Baldwin 2003). Our reliance on aggregated budgets for forage cost estimation makes assessment of rising costs for energy and water for grazing intensification problematic. The energy (fossil fuel) component for treated alfalfa production, treated irrigated pasture, and treated, nonirrigated range forages, respectively, is on the order of 23%, 9%, and 4% of total operating costs for the budgets we used. Our sensitivity analysis indicates that while the optimal forage mixes are remarkably stable in response to a doubling of energy costs, the representation of treated irrigated pasture—in particular—appears to be most susceptible to further increases in energy costs, followed by that for the treated alfalfa. This ranking is affected by differences in productivity (pasture being lower) as well as ranch size. This indicates that increases beyond a doubling of fuel costs for the intensification of forage production could jeopardize sustainability especially if technological improvements in forage yields fail to keep pace. Water is even more difficult to assess than energy in this regard. Water costs are rarely explicit in forage budgets, and, historically for Utah, water has been subsidized and costs tend to be low (on the order of 2–3% of total variable costs of production).

IMPLICATIONS

Again, model results require empirical validation. In general, however, this work supports the idea that irrigated forage systems can have very high utility in certain situations, even when challenged by drought. Diverse forage resources and larger operational sizes promote profitability and risk management.

More technical work on the efficacy of intensive, irrigated grazing systems is needed under more varied conditions. More understanding is needed as to how producers make strategic planning decisions, especially with respect to drought management, resource conservation, and the efficiency of livestock marketing. Prominent policy considerations for drought mitigation include how to best promote sustainable hay markets and whether public lands could play an enhanced role in terms of providing fodder banks in certain situations. Capital and labor constraints that preclude implementation of improved forage systems need to be clarified. Finally, to what extent producers even in mesic environments can sustain intensified forms of resource use, given increasing urban and rural water demands as well as climbing costs of fossil fuels, requires further investigation.

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APPENDIX

This appendix contains Table A1, which displays variables used in the Linear INteractive Discrete Optimizer (LINDO) multiperiod linear programming model, followed by equations used in the LINDO model, as well as Table A2, which gives detailed descriptions of the major nonirrigated and irrigated forage types considered in the analysis.

Table A1. Variables, coefficients, and subscripts used in the LINDO model.

Variables and subscripts	Definition
Variables	
A	Animals for sale
F	Feed type utilized by animals
π	Returns net of feed costs
S	Saleable feed type
T	Labor required per animal unit
X	Initial number of cows in brood herd
Y	Various forage acreage limits
Z	Animal unit month (AUM) limit
ACR	Total acreage available
AFT	Aftermath (from treated and untreated hay)
AUM	Seasonal AUM requirement
AUMT	Yearly total of AUMs
BAR	Barley
BHAY	Purchased hay
BULL	Bull breeding stock
CBULL	Cull bull
CCOW	Cull cow
COW	Brood cow, base unit
DR	Desert range
HAY	Alfalfa hay
HFRA	Feeder heifer calves
HFRB	Replacement heifers
HFRC	Yearling heifers
HOR	Horses
NR	Returns net of feed costs
PP	Public land grazing permits
SBAR	Saleable barley
STRA	Feeder steer calves
STRB	Yearling steers
SHAY	Saleable untreated and treated hay
THAY	Treated alfalfa hay feed
TLAB	Total labor hours
TLF	Treated lower foothill
TPAS	Treated pasture
TUF	Treated upper foothill
TWM	Treated wet meadow
UHAY	Untreated alfalfa hay feed
ULF	Untreated lower foothill
UPAS	Untreated pasture
UUF	Untreated upper foothill
UWM	Untreated wet meadow
α, β, δ, γ, λ, σ, ψ	Various coefficient values
Subscripts	
h	
Animals sold	1 = steer calves
	2 = heifer calves
	3 = yearling steers
	4 = yearling heifers
	5 = cull cows
	6 = cull bulls
Animals not sold	7 = replacement heifers
	8 = cows
	9 = bulls
	10 = horses
i	
Season	1 = winter, December–February
	2 = spring, March–May
	3 = summer, June–August
	4 = fall, September–November
j	
Year	1 through 11
k	
Saleable feed	1 = untreated hay
	2 = treated hay
	3 = barley
l	
Feed used	1 = untreated hay
	2 = treated hay
	3 = untreated pasture
	4 = treated pasture

Table A1. Continued.

Variables and subscripts	Definition
	5 = barley
	6 = aftermath
	7 = untreated wet meadow
	8 = treated wet meadow
	9 = untreated upper foothill
	10 = treated upper foothill
	11 = untreated lower foothill
	12 = treated lower foothill
	13 = desert range
	14 = public land permits
	15 = purchased hay

Objective Function

$$MAX\ \Pi: \sum_{h=1}^{6}\sum_{i=1}^{4}\sum_{j=1}^{11}\alpha A_{hij} + \sum_{k=1}^{3}\sum_{i=1}^{4}\sum_{j=1}^{11}\beta S_{kij} - \sum_{l=1}^{15}\sum_{i=1}^{4}\sum_{j=1}^{11}\gamma F_{lij}, \quad [1]$$

where maximum returns net of feed cost (Π) is assumed to be a function of animal price (α) times animal type (A) plus sold feed value (β) times quantity of feed sold (S) less the cost (γ) of producing feed fed (F) with subscripts h = animal, i = season, k = feeds sold, and j = years.

Ranch Operation Equations of Motion

Cow herd growth or decline in consecutive years:

$$COW_{4j-1} - 1.15COW_{lj} \leq 0 \quad [2]$$

(cow herd size in the fourth quarter of year j can be at maximum 1.15% larger than in year $j-1$).

$$COW_{4j-1} - 0.85COW_{lj} \geq 0 \quad [3]$$

(cow herd size in the fourth quarter of year j can be at maximum, 85% smaller than in year $j-1$).

Seasonal animal unit month (AUM) requirements:

$$\sum_{h}\lambda A_{hij} - AUM_{ij} = 3.0COW_{ij} + 3.0CCOW_{ij} + 4.5HORS_{ij} + 3.6BULL_{ij} + 3.6CBULL_{ij} + 0.35STRA_{ij} + 2.01STRB_{ij} + 0.35HFRA_{ij} + 2.01HFRB_{ij} + 2.01HFRC_{ij} - AUM_{ij} = 0, \quad [4]$$

where λ = seasonal AUMs required by animal (A) and AUM = seasonal total, with the subscripts h = animal type, i = season, and j = year.

Seasonal cow-to-bull, cow-to-horse, cow-to-cull cow, and bull-to-cull bull ratios:

$$COW_{ij} - 20BULL_{ij} = 0, \quad [5]$$

where a breeding bull ($BULL$) is required to service every 20 cows (COW) with i = season and j = year;

$$COW_{ij} - 50HORS_{ij} = 0, \quad [6]$$

where each horse ($HORS$) is capable of working 50 cows (COW) with i = season and j = year;

$$6.7CCOW_{ij} - COW_{ij} = 0, \quad [7]$$

where a herd rotation requires one cull cow ($CCOW$) for every 6.67 herd cows (COW) for a cull rate of 15% with i = season and j = year;

$$3.3CBULL_{ij} - BULL_{ij} = 0, \quad [8]$$

where bulls ($BULL$) are culled ($CBULL$) every three years with subscripts i = season and j = year.

Seasonal cow-to-saleable steer ratio:

$$STRA_{ij-1} + STRB_{ij} - 0.45COW_{ij-1} = 0, \quad [9]$$

where $STRA$ in season i, year $j-1+STRB$ in season i, year j, must equal 45% of the breeding cows in season i, year $j-1$.

Seasonal cow-to-saleable heifer ratio:

$$HFRA_{ij-1} + HFRC_{ij} - 0.30COW_{ij-1} = 0, \quad [10]$$

where $HFRA$ in season i, year $j-1+$HFRC in season i, year $j-1$, must equal 30% of the breeding cows in season i, year $j-1$.

Seasonal cow-to-replacement heifer ratio:

$$HFRB_{ij} - 0.15COW_{ij-1} = 0, \quad [11]$$

where HFRB (replacement heifers) in season I, year j, must equal 15% of the breeding cows in season I, year $j-1$.

Forage Equations of Motion

AUMs available by season for each land, crop, and treatment type:

$$\sum_{l}\psi F_{lij} - AUM_{ij} = 0, \quad [12]$$

where the level of production for each feed (ψ) times the acreage produced (F) must equal the total AUMs for each season with subscripts l = feed type, i = season, and j = year.

Irrigated cropland acreage limitations:

$$\sum_{l}\sum_{i}F_{lij} + \sum_{k}\sum_{i}S_{kij} \leq Y, \quad [13]$$

where the feed fed (F) plus the forage sold (S) is less than or equal to total irrigated acreage available with subscripts l = feed type, i = season, and j = year.

Other land constraints:

$$\sum_i (UWM_{ij} + TWM_{ij}) \leq Y, \quad [14]$$

where untreated wet meadow plus treated wet meadow is less than or equal to the total wet meadow available with subscripts i = season and j = year;

$$\sum_i (ULF_{ij} + TLF_{ij}) \leq Y, \quad [15]$$

where untreated lower foothill (ULF) and treated lower foothill (TLF) is less than or equal to an acreage limitation (Y) with i = season and j = year;

$$\sum_i (UUF_{ij} + TUF_{ij}) \leq Y, \quad [16]$$

where untreated upper foothill (UUF) plus treated upper foothill (TUF) is less than or equal to an acreage limitation (Y) with i = season and j = year;

$$\sum_i DR_{ij} \leq Y, \quad [17]$$

where desert range (DR) used in each season and year must be less than or equal to the desert range (Y) available with i = season and j = year;

$$PP_{ij} \leq Y, \quad [18]$$

where public permits (PP) in season (i), year (j), must be less than or equal to the total seasonal amount available (Y).

Public permit constraint to prevent nonuse in consecutive years:

$$PP_{ij-1} + PP_{ij} + PP_{ij+1} \geq Z, \quad [19]$$

where public permits (PP) in season (i), year ($j-1$) plus PP in season i, year j, plus PP in season i, year ($j+1$), must be greater than or equal to two times the annual seasonal level available (Z).

Carrying-over steer and heifer calves to sell as yearlings:

$$STRB_{ij} - STRA_{ij-1} \leq 0, \quad [20]$$

where $STRB$s in season i and year j would be less than or equal to the $STRA$s in season i, year $j-1$;

$$HFRC_{ij} + HFRB_{ij} - HFRA_{ij-1} \leq 0, \quad [21]$$

where $HFRC$s plus $HFRB$s in season i, year j, must be less than or equal to $HFRA$s in season i, year $j-1$.

Accounting Equations

Revenue net of feed costs each year:

$$NR_j - \left(\sum_h \alpha A_{ihj} + \sum_k \sum_i \beta S_{ki} - \sum_l \sum_i \gamma F_{ijl} \right) = 0, \quad [22]$$

where returns net of feed costs (NR) less {animal revenues (αA) + feed sold revenues (βS) less cost of feeds fed (γF)} must equal zero with h = animal type sold, k = feed sold, j = year, and i = season.

Aftermath availability from cropped hay acreage (AUMs):

$$\sum_i \left(AFT_{ij} - THAY_{ij} - UHAY_{ij} - SHAY_{ij} \right) = 0, \quad [23]$$

where aftermath (AFT) available is equal to the treated hay ($THAY$) plus untreated hay ($UHAY$) plus hay sold ($SHAY$) with i = season, j = year.

Crop rotation constraint:

$$\sum_i \left(THAY_{ij} + UHAY_{ij} + SHAY_{ij} + TPAS_{ij} + UPAS_{ij} \right) - \sum_i \left(6.7BAR_{ij} + 6.7SBAR_{ij} \right) \geq 0, \quad [24]$$

where [treated hay ($THAY$) plus untreated hay ($UHAY$) plus sold hay ($SHAY$)] must equal the barley fed (BAR) plus barley sold ($SBAR$) with i = season and j = year.

Total annual AUMs available from feed fed:

$$\sum_i \sigma F_{lij} - AUM_{ij} = 0, \quad [25]$$

where the sum of all feeds fed (F) must equal the animal AUM requirements with l = feed type, i = season, and j = year.

Constraints on crop availabilities:

$$\sum_i \left(TPAS_{ij} + UPAS_{ij} \right) = 0 \quad \text{for } i = 1,4, \quad [26]$$

where treated and untreated pastures (TPAS and UPAS) are not available in seasons 1 and 4 with i = season and j = year;

$$\sum_i AFT_{ij} = 0 \quad \text{for } i = 1,2,3, \quad [27]$$

where aftermath (AFT) is unavailable except during season 4 with i = season and j = year;

$$\sum_i \left(TWM_{ij} + UWM_{ij} \right) = 0 \quad \text{for } i = 1,4, \quad [28]$$

where treated wet meadow (TWM) and untreated wet meadow (UWM) are unavailable in seasons 1 and 4 with i = season and j = year;

$$\sum_{i}\left(TUF_{ij}+UUF_{ij}\right)=0 \quad \text{for } i=1,4, \qquad [29]$$

where treated upper foothill (TUF) and untreated upper foothill (UUF) are unavailable during seasons 1 and 4 with i = season and j = year;

$$\sum_{i}\left(TLF_{ij}+ULF_{ij}\right)=0 \quad \text{for } i=1,4, \qquad [30]$$

where treated lower foothill (TLF) and untreated lower foothill (ULF) are unavailable during seasons 1 and 4 with i = season and j = year.

Total labor required by animal type:

$$TLAB_j-\sum_{h}\delta T(A_{jh})=TLAB_j-1.0TCOW-1.0TCCOW$$
$$-0.75TSTRB-0.75THFRB-0.75THFRC=0, \qquad [31]$$

where total annual labor required ($TLAB_j$) must equal the monthly labor requirement (δ) times the total number of AUMs corresponding to each animal type (TA_{jh}) with j = year and h = animal type; total labor hours for $STRA$ and $HFRA$ are captured within the COW variable; and labor required for producing individual crops is included in the respective budgeted costs.

Table A2. Descriptions of forage types for Utah beef operations.[1]

Forage type	Description
Desert range	Nonirrigated, native shrub and grass range, often in late seral ecological condition, to be used during October through January. Average annual precipitation is 18 cm. Native grasses include Indian ricegrass (*Achnatherum hymenoides*), bottlebrush squirreltail (*Elymus elymoides*), blue grama (*Bouteloua gracilis*), sand dropseed (*Sporobolus cryptandrus*), and alkali sacaton (*Sporobolus airoides*) interspersed among scattered woody plants [shadscale (*Atriplex confertifolia*), four-wing saltbush (*Atriplex canescens*), and sagebrush (*Artemesia tridentata*)]. Soils are of poor to moderate production capability. Low input management. Animals graze sites continuously during winter, and some forage has been lost to weathering. Less than 20% of forage nutritional value is available in winter compared to that of spring and summer. Recommended utilization is below 60% assuming plants are dormant.
Untreated upper-foothill range	Nonirrigated native range, often in poor to moderate condition. Includes public and private land. Native grasses include Western wheatgrass (*Pascopyrum smithii*), bluebunch wheatgrass (*Pseudoroegneria spicata*), and Indian ricegrass (*A. hymenoides*) interspersed within moderate to dense stands of sagebrush (*A. tridentata*), bitterbrush (*Purshia tridentata*), and four-wing saltbush (*A. canescens*). Most grasses are unable to persist under heavy grazing. Sites are located in upland areas with higher capacity soils. Low input management. Average annual precipitation is 30–38 cm. Cattle are often grazed on a continuous basis, with some rotations employed. Most use occurring in spring and summer seasons. Ninety percent of the forage is available in midspring to early summer for about four months. Recommended utilization should not exceed 60%. Treated upper foothill range is similar to untreated but has a mix of native and introduced drought-tolerant species such as bluebunch wheatgrass (*P. spicata*), intermediate wheatgrass (*Thinopyrum intermedium*), desert wheatgrass (*Agropryon desertorum*), and crested wheatgrass (*Agropyron cristatum*). Moderate levels of vegetation management have occurred. Brush control has been performed. Forage availability and utilization rates are similar to those of untreated sites.
Untreated lower-foothill range	This differs from upper foothill range in that past vegetation manipulations have often been performed, but have not been maintained. These sites are often in poor to moderate condition and all are nonirrigated. Native grasses are mixed with patches of crested wheatgrass that have been moderately encroached by *Artemesia* spp. and herbaceous plants. Sites occur at lower elevations with heavier soils compared to upper foothill range. Animals graze sites continuously during spring and early summer. Ninety percent of forage is available in midspring to early summer. Utilization should not exceed 60%. Treated lower foothill range is similar to untreated, but crested wheatgrass has been planted and maintained. Brush has been periodically controlled.
Untreated native wet meadow	This typically has heavier clayey soils that are poorly drained and have minor to moderate sodium concentrations. Includes open meadows and riparian sites (subirrigated). Plants are a complex of grasses, sedges (*Carex* spp.), and rushes (*Juncus* spp.). There is no application of fertilizers. Animals graze on a continuous basis during the growing season. Forage availability and quality are excellent early in the growing season and moderate to low by mid summer and fall. Utilization should not exceed 80%.
Treated wet meadow	Similar to untreated, but treated sites tend to have higher-quality, better-drained soils. This accommodates addition of improved grasses such as bromes (*Bromus* spp.), orchardgrass (*Dactylis glomerata*), bluegrasses (*Poa* spp.), tall fescue (*Festuca* spp.), and meadow foxtail (*Alopecurus arundinaceus*). One application of 124–173 kg N $\cdot$ ha^{-1} is made in the early spring. Some land preparation may be required. Animals graze the unit on a continuous basis. These sites tend to be on private land.
Untreated (or poorly managed) irrigated pasture	Occurs on fairly level sites with excellent soils and plant growing conditions. These sites occur on private lands and plantings of moderately drought-resistant species such as bromes (*Bromus* spp.), Kentucky bluegrass (*P. pratensis*), and intermediate wheatgrass have occurred to some extent. Forage quality is moderate to good. There are no shrubs. Adequate irrigation water is present during the early to mid–growing season with less availability after midsummer. Animals graze the unit on a continuous basis during the growing season. Limited application of fertilizer occurs in early spring, with 124–173 kg N $\cdot$ ha^{-1}. Forage availability at the start of the season is excellent, but declines markedly after midsummer. Utilization should not exceed 80%.

Table A2. Continued.

Forage type	Description
Treated (well-managed) irrigated pasture	Includes more extensive plantings of improved grasses such as meadow brome (*Bromus riparius*), orchardgrass, tall fescue (*Schedonorus phoenix*), and timothy (*Phleum pratense*). There is also active use of herbicides. Irrigation water is available throughout the growing season. Two applications of 124 kg N $\cdot$ ha^{-1} occur in the spring and during the middle of the growing season. Animals are appropriately stocked and graze different paddocks monthly on a rotational basis. Forage is plentiful in early to mid–growing season, but begins to decline by midsummer.
Untreated alfalfa (*Medicago sativa*)	This consists of poorly managed, average-yielding stands under moderate input levels. Includes older stands having adequate irrigation.
Treated alfalfa (*M. sativa*)	Adequately tilled and fertilized. Herbicides are used. Irrigation is adequate. The best available alfalfa variety is used. Aftermath is alfalfa hay stubble on irrigated sites that is grazed in the fall season.
Barley (*Hordeum vulgare*)	This consists of grain produced from irrigated fields. Barley is the preferred grain crop for supplemental feeding of cattle in the fall and is usually fed in a rolled form. Barley is also an important component of the alfalfa rotation in Utah.

[1]Descriptions of forage sites are based on expert opinions (H. Horton, personal communication, September 2004; R. Banner, personal communication, December 2006). Plant nomenclature follows USDA–NRCS (2007) PLANTS database (http://plants.usda.gov/index.htm).