A Case Study for Optimal Allocation of Range Resources

SANDY A. D'AQUINO

Highlight: *A linear programming model was developed to help in the management of range resource systems. This analysis simultaneously considers per acre management costs and resulting per animal gross revenues. The management plan sets out a season-by-season use of land areas and associated forage resources with the objective of maximizing net dollar returns. Procedures developed in this study may also be applied to public resource management problems.*

A problem of resource management is to allocate resources in such a manner as to either arrive at a level of product output that will maximize returns, or to determine the most efficient combination of resources that will supply a specified level of product output. The range resources may include land and associated forages, human labor, and supplemental feeds.

The purpose of this study was to develop a methodology for handling allocation of resources in an economic system where all information associated with their productivity are presumed known and constant. For any given period in time, therefore, no variation is considered. Although this is obviously an oversimplified assumption, it does allow the resource system to be presented to a framework that assists resource managers to develop optimal plans for their particular situations. Procedures developed in this study may be applied to public resource management problems by determining the costs of supplying specified quantities of public goods (hunting, fishing, camping, etc.).

Description of Study Area

The study area was the Eastern Colorado Range Station (ECRS), located midway between Akron and Sterling, Colorado. The total area was approximately 3,717 acres with an elevation averaging 4,275 ft. The study area, although a research station on the central Great Plains belonging to the State of Colorado, was treated as a private enterprise, and analysis was confined to decision making within the market system.

Soils are representative of sandhill range on the central Great Plains. Thus, a management plan specifically designed for the ECRS may be applicable on many other sites of the central Great Plains. Average annual rainfall is 15.30 inches; 70% occurs between May 1 and October 1 (Sims and Denham, 1969). Production rates and optimal utilization of forage are heavily dependent on rain during the growing season.

Components of the Management Model

In order to achieve optimal allocation of a resource system, the following model was developed that allowed for the allocation of resources so as to maximize contribution margin;[1]

$$z_{max} = \sum_{j=1}^{n} r_j y_j - \sum_{j=1}^{m} c_j x_j \qquad (1)$$

where:

- n = number of final products under consideration;
- r_j = gross dollar value of each final product for $j=1,2,...,n$;
- y_j = number of units of each final product for $j=1,2,...,n$;
- m = number of possible management alternatives in the problem;
- c_j = cost per unit of each management alternative for $j=1,2,...,m$; and
- x_j = number of units of each specified management alternative for $j=1,2,...,m$.

The decision-making model was set in a linear programming framework (Fig. 1) with the objective function:

$$z_{max} = \mathbf{q}\,\mathbf{x} \qquad (2)$$

where **q** is composed of variable costs (**d**) and gross revenues (**g**), and **x** is made up of alternatives listed within **t** and **f** in Fig. 1. The third equation, $\mathbf{A}\,\mathbf{x} \leqslant \mathbf{b}$, summarizes the remaining components of the linear programming model. **A** is comprised of subcomponents **H**, **J**, **C**, **I**, **M**, and **N**; **x** is comprised of **t** and **f**; and, **b** is made up of **a**, **e**, and **v** in Fig. 1. A fourth equation, $\mathbf{x} \geqslant 0$, indicates that all variables in the model must be greater than or equal to zero. There may, however, be cases when a management alternative is designed to increase the utilization of resources for one product but thus cause a decline in the production of a second product.

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Editor's Note: This article and the one following, "A Serial Optimization Model for Ranch Management" by E. T. Bartlett, Gary R. Evans, and R. E. Bement, present recently developed analytical models that could facilitate study of alternatives for multiple uses in natural resource management. Knowledge of linear programming would be helpful to fully understand the data organization in Figure 1 as explained. A good reference to linear programming is Wagner, Harvey, M., 1969, *Principles of Operations Research*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey. Computer analysis of data can be accomplished by using programs, of which there are many, readily available in most computer program libraries. Two programs being used by land managers are OPTIMIZE developed by Colorado State University and RCS (Resource Capability System) developed by the Forest Service, U.S. Department of Agriculture. The reader is referred to the reference D'Aquino (1972) for more detail of the material presented.

[1] Contribution margin is gross dollar returns minus variable costs; variable costs are those which vary with changes in the use of alternative management schemes. In order to arrive at net dollar returns (net profits), contribution margin must be adjusted for fixed costs. By definition, fixed costs remain constant over a specified time interval with respect to a designated management plant for a resource system.

Table 1. Management alternatives for different quantities of soil types, croplands, and supplemental feed and products considered in the management plans.

Management alternative number	Classification basis	Season	Quantity
	Soil type		
1–5	Deep sand	1–5	2,115 acres
6–10	Sandy plains	1–5	849 acres
11–15	Loamy plains	1–5	291 acres
16–18	Alfalfa cropland	1, 2, 5	146 acres
19–22	Sorghum cropland	1, 2, 3, 5	315 acres
	Supplement		
23–27	Cottonseed cake	1–5	40,000 lb
28–32	Mineral block	1–5	40,000 lb
33–37	Corn	1–5	40,000 lb
38–42	Wheat	1–5	40,000 lb
43–47	Beet pulp	1–5	40,000 lb
	Product		
48	Cow-calf	1–5	
49	Steers	1–5	
50	Steers	5	
51	Steers	1–4	
52	Steers	1–3	

Description of Management Model and Incorporation of Ranch Data

Components of the management model, as shown in Figure 1, were compiled with data from the ECRS. To determine the contribution margin from a specific management plan, the elements within **d** and **g** are multipled by elements in **t** and **f**. Elements within **t** are all the types of management alternatives considered in the ECRS plan. Alternatives might include continuous versus rotation grazing, brush control and reseeding, fertilization, supplemental feeds, crop harvesting versus crop grazing, and a do-nothing alternative. In our model there were 47 possible management alternatives (Table 1) consisting of five grazing seasons for each soil type, cropland acreages, and supplemental feeds.[2] Elements within **f** indicate the various kinds of products to be considered in the management plan. Products that may be considered are cow/calf units, steers during different seasons, and the native animal population. If a product is to be considered in a given resource system, it must be entered within **f**. In our case, five products were considered (Table 1).

Elements within **a** list the available fixed or nonrenewable resources plus the quantity of supplemental feed (Table 1). Included are soil series and topography and a variety of supplemental feeds that may be utilized for their specific nutrient content. A soil type with relatively high productivity should be considered a separate fixed resource from a soil type with lower productivity.

Management alternatives utilize fixed resources, and their amount available cannot be exceeded. **C** is the linkage between the management alternatives and the land resources and supplemental feed limitations. When a management alternative is designed for the fixed resource being considered, a *one* (1) is placed in **C** and the management alternative is then included for analysis.

[2] Since quantity and nutrient content of available forage varied during the year, the grazing year was divided into five seasons: (1) Season 1—early spring—April 1 to May 15; (2) Season 2—late spring—May 16 to June 30; (3) Season 3—early summer—July 1 to August 31; (4) Season 4—late summer—September 1 to September 30; and (5) Season 5—fall-winter—October 1 to March 31.

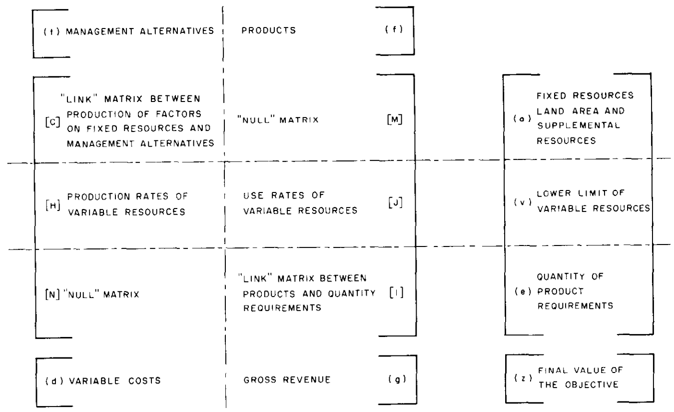

Fig. 1. *Components of a linear programming resource management model.*

Model components **H**, **J**, and **v** are concerned with renewable resources. Elements within **H** give production rates in pounds of dry matter, protein, and phosphorus per acre of rangeland and cropland (Table 2) and the percentage of dry matter, protein and phosphorus per pound of supplemental feed (Table 3). Nutrient content of range forage and supplemental feeds were obtained from Cook and Harris (1968), Sims et al. (1971), and Morrison (1959). Each of the management alternatives modifies the production rate of the renewable resources. The model allows for the use of those management alternatives that contribute the greatest increase in the production output per unit cost.

Elements within **J** set out utilization rates of available dry matter, protein and phosphorus for the products under consideration. This set of cells is paired with the set of appropriate production rates in **H**. Entries in **H** are positive since they add to available dry matter, protein, and phosphorus. Entries in **J** are all negative since dry matter, protein, and phosphorus are used up in production. The accepted daily nutrient requirements for product outputs are shown in Table 4 (National Academy of Science, 1963).

Elements with **v** designate the lower limit of use of renewable resources and supplemental feeds. In this study, all

Table 2. Dry matter, protein, and phosphorus content (lb/acre) on the range sites and cropland by seasons.

	Season				
Site and nutrient	1	2	3	4	5
Deep sand					
Usable dry matter	491.00	591.00	817.00	651.00	522.00
Protein	43.01	74.47	58.82	34.46	21.40
Phosphorus	.78	1.65	1.63	1.11	0.47
Sandy plains					
Usable dry matter	637.00	681.00	840.00	774.00	687.00
Protein	28.03	83.08	59.69	38.70	29.48
Phosphorus	0.38	1.63	1.85	1.32	0.55
Loamy plains					
Usable dry matter	420.00	449.00	555.00	511.00	453.00
Protein	43.68	63.76	42.74	30.15	17.67
Phosphorus	0.71	1.39	1.28	0.66	0.36
Alfalfa cropland					
Usable dry matter	3950.00	3950.00			3950.00
Protein	1000.00	1000.00			1000.00
Phosphorus	12.50	12.50			12.50
Sorghum cropland					
Usable dry matter	1740.00	1740.00	1740.00		3354.00
Protein	138.00	138.00	138.00		265.20
Phosphorus	3.60	3.60	3.60		5.85

Table 3. Dry matter, protein, and phosphorus content (%) of supplemental feeds.

Supplemental feeds	Dry matter	Protein	Phosphorus
Cottonseed cake	94.0	25.0	0.99
Mineral block	0.0	0.0	6.00
Corn	97.0	6.0	0.40
Wheat	90.0	15.6	0.40
Beet pulp	91.0	1.6	0.10

entries in **v** were zero because the quantities consumed of dry matter, protein, and phosphorus were required to be less than or equal to the quantities available.

The quantity of product output requirements to be considered were listed in **e**. In this study, all cells within **e** contained zeros. This simply states that the model allowed the program to select whatever quantity of the various product outputs that resulted in maximum contribution margin from the use of the resource system. The only constraint was that no product could have a negative output value.

Elements within **I** link the product types to their quantity requirement (**e**) and to their gross revenues (**g**). **M** and **N** are groups of zeros needed to complete the total matrix of the management model.

The final parts of the model make up the objective function. Elements within **d** designate the costs associated with each management alternative. In this study all management alternatives have only cost. The gross revenues were measured in final product output. Thus, the model is not concerned with maximizing dollar returns from any single management alternative but, instead, is concerned with management and dollar returns from the entire resource system. The costs listed in **d** are directly associated with managing an acre of rangeland per year, cultivating and/or harvesting acres of cropland per year, and the purchasing of supplemental feeds (Table 5).

The gross revenues associated with the product outputs are listed in **g**. The gross revenues are based on expected weight gains and expected sale prices for the various products during the various seasons (Table 6).

In this study, **z** denotes the maximum contribution margin. However, if the purpose was to allocate resources at the least probable cost to produce a specified quantity of product(s), **z** would denote the least cost. No matter what the purpose is in utilizing the resource system, fixed costs are incurred (Table 7). Whereas variable costs are adjusted for during the actual computing of the management plan, fixed costs must be adjusted for after the optimal management plan is selected. When we adjust the contribution margin for fixed costs, the resulting net dollar returns are, in fact, net revenues (net profits).

Table 5. Costs associated with management of rangeland, cultivating and/or harvesting cropland, and purchase of supplemental feeds.

Land feed category	Cost ($)[1]
Deep sand management	0.30/acre/year
Sandy plains management	0.30/acre/year
Loamy plains management	0.30/acre/year
Alfalfa cropland–hay	15.00/acre/year
Sorghum cropland–silage	12.00/acre/year
Sorghum cropland–grazed	6.00/acre/year
Cottonseed cake	0.052/lb
Mineral block	0.027/lb
Corn	0.032/lb
Wheat	0.025/lb
Beet pulp	0.030/lb

[1] Based on 1971 prices.

Management Plans

The model was used as a framework for evaluating two alternative management plans; (I) optimal use of available resources without supplemental feeds; and (II) the same as (I) except the constraint on supplemental feeds was arbitrarily set at 40,000 pounds. The results from both management plans are returned in terms of 82 variables and are listed in Table 8.

The first 22 variables (X_1 - X_{22}) are management alternatives associated with acres of rangeland grazed in each season and acres of cropland allocated for use in each season. The next 25 variables (X_{23} - X_{47}) are associated with controlled use of supplemental feeds for the various seasons. In Plan I, since no supplemental feeds were used, all entries are zero. The next five variables (X_{48} - X_{52}) designate the quantity of various products that are produced in order to have optimal use of the resource system. Finally, an additional 30 variables (X_{53} - X_{82}), known as slack variables, are listed. Slack variables denote unused quantities of various types of

Table 4. Livestock requirements for phosphorus, protein, and dry matter (lb/animal/season).

		Product				
			Steer			
Requirements	Season	Cow/calf	Year-round	Season 5	Season 1–4	Season 1–3
Phosphorus per season	1	2.25	1.35		1.35	1.35
	2	2.25	1.31		1.31	1.31
	3	3.00	1.74		1.74	1.74
	4	1.50	0.87		0.87	
	5	5.40	3.60	3.60		
Protein per season	1	103.50	58.50		58.50	58.50
	2	103.80	67.50		67.50	67.50
	3	138.00	90.00		90.00	90.00
	4	69.00	45.00		45.00	
	5	252.00	234.00	234.00		
Dry matter per season	1	1260.00	643.50		643.50	643.50
	2	1260.00	859.50		859.50	859.50
	3	1680.00	1146.00		1146.00	1146.00
	4	840.00	573.30		573.30	
	5	3240.00	2268.00	2268.00		

Table 6. Weights, prices, and gains of livestock and associated revenue from product sales.

Product	Weight at purchase (lb)	Price/lb at purchase (cents)	Weight[1] gain/day (lb)	Weight at sale (lb)	Price/lb[2] at sale (cents)	Gross revenue ($/head)
Calf[3]	70	–	1.5	458	28.80	120.00
Steers–year round	500	25.36	1.5-1.7	1068	24.10	120.39
Steers–season 5	500	23.90	1.5	733	24.10	62.00
Steers–seasons 1-4	500	25.36	1.7	812	23.90	63.08
Steers–seasons 1-3	500	25.36	1.7	760	25.83	65.50

[1] Averaged weight of all purchased stock.
[2] Livestock prices are based on 11-year average (1959-1969).
[3] Each calf unit required feed from the mother cow.

resources and associated excess quantities of dry matter, protein, and phosphorus.

Output from the computer program indicated the maximum contribution margin under Plan I would be obtained by grazing 832 steers from October 1 to March 31 on 686 acres of sandy plains, 315 acres of unharvested sorghum cropland, and 90 acres of harvested alfalfa cropland. On April 1, all the steers would be sold and a new herd of 694 steers would be purchased. Their grazing schedule would be: April 1 to May 15, 164 acres of sandy plains, 291 acres of loamy plains and 56 acres of harvested alfalfa cropland; May 16 to June 30, 1,052 acres of deep sand; July 1 to August 31, 1,063 acres of deep sand. At the end of this period, the steers would be sold. The calculated contribution margin for the entire operation would be $92,003. When adjusted for $31,505 of fixed costs, the net profit would be $60,498.

The slack variables for each resource constraint are helpful in explaining how management alternatives and product requirements are handled. X_{53} – X_{57} are slack variables denoting the number of acres of rangeland and cropland left unused in the management plan (Table 8). In Plan I, X_{53} – X_{57} were all zero. This means that all available land acreage was used. X_{58} – X_{62} were slack variables that designated quantities of supplemental feed that were available but not used. In Plan I, X_{58} – X_{62} were all zero since no supplemental feeds were considered for use.

Variables X_{63} – X_{77} showed that there was an excess of phosphorus, protein and/or dry matter in at least one of the five seasons. There was unused phosphorus in every season except Season 4. Seasons 1 and 2 had unused protein; and, there was excess dry matter in Season 3.

Whenever an excess of dry matter exists in a season, consideration should be given to use of supplemental feeds. An excess of dry matter denotes a shortage of nutrient in that particular season; i.e., a shortage of protein and/or phosphorus. Examination of slack variables in Season 3 showed an excess of phosphorus but not of protein. This suggested the need for a protein supplement to allow livestock (products) to utilize the excess dry matter. Cottonseed cake and wheat supplements had the highest percentage of protein; nevertheless the program was allowed to select from all supplemental feeds (Table 1).

In Plan II constraints on supplemental feeds were arbitrarily set to be a maximum of 40,000 pounds. Cottonseed cake and wheat were the only supplemental feeds used in Season 3. With the use of supplemental feeds, output from the computer program indicated that maximum contribution margin would now be obtained by grazing 817 steers from October 1 to March 31 on 651 acres of sandy plains, 315 acres of unharvested sorghum cropland, and 89 acres of harvested alfalfa cropland. On April 1, all the steers would be sold and a new herd of 744 steers would be purchased. Their grazing schedule would be: April 1 to May 15, 199 acres of sandy plains, 291 acres of loamy plains, and 57 acres of harvested alfalfa cropland; May 16 to June 20, 1,128 acres of deep sand; July 1 to August 31, 987 acres of deep sand; 10,574 pounds of cottonseed cake supplement, and 40,000 pounds of wheat supplement. For Plan II, the grazing herds would be assigned to pastures as shown in Figure 2. At the end of the summer

Table 7. List of fixed costs for management of Akron Ranch.

Item	Cost ($)
Depreciation on equipment and buildings (10%/year)	2,610
Repairs, gas, oil for vehicles	1,500
Labor: Manager for Akron Ranch	15,000
Hired hand (75% of $5,00)	3,750
Water development	680
Veterinarian expenses	2,200
Rental on land	1,886
Taxes	2,352
Transportation costs for livestock	927
Miscellaneous	600
Total fixed costs	$31,505

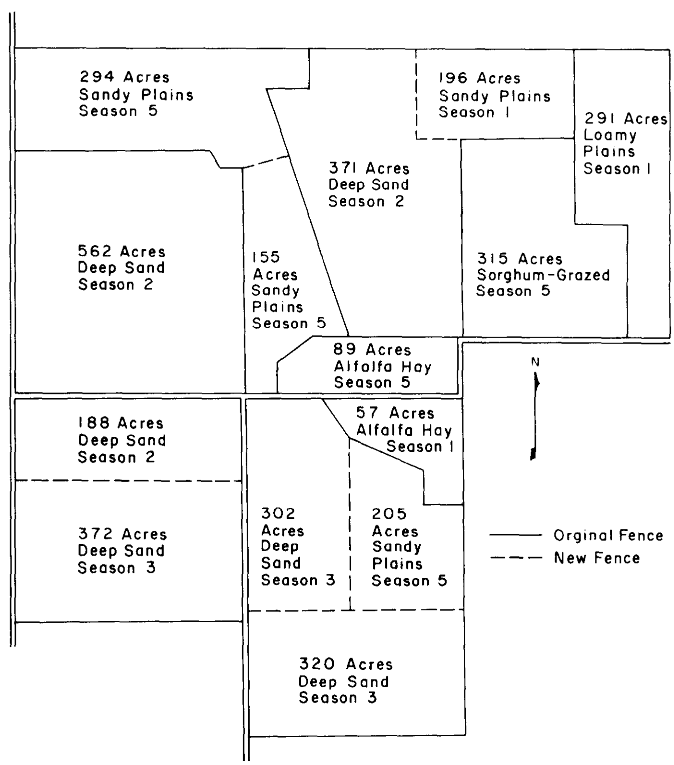

Fig. 2. *Pasture plan for the Eastern Colorado Range Station, Akron, Colo.*

Table 8. Results from computer program executions–list of 82 variables in two management plans for the Eastern Colorado Range Station.[1]

Alternative code	Solution 1	Solution 2	Alternative definition
X 1 =	0	0	Deep sand acs used Season 1
X 2 =	1052	1121	Deep sand acs used Season 2
X 3 =	1063	994	Deep sand acs used Season 3
X 4 =	0	0	Deep sand acs used Season 4
X 5 =	0	0	Deep sand acs used Season 5
X 6 =	164	196	Sandy plains acs used Season 1
X 7 =	0	0	Sandy plains acs used Season 2
X 8 =	0	0	Sandy plains acs used Season 3
X 9 =	0	0	Sandy plains acs used Season 4
X 10 =	686	654	Sandy plains acs used Season 5
X 11 =	291	291	Loamy plains acs used Season 1
X 12 =	0	0	Loamy plains acs used Season 2
X 13 =	0	0	Loamy plains acs used Season 3
X 14 =	0	0	Loamy plains acs used Season 4
X 15 =	0	0	Loamy plains acs used Season 5
X 16 =	56	57	Alfalfa hay acs used Season 1
X 17 =	0	0	Alfalfa hay acs used Season 2
X 18 =	90	89	Alfalfa hay acs used Season 5
X 19 =	0	0	Sorghum silage acs used Season 1
X 20 =	0	0	Sorghum silage acs used Season 2
X 21 =	0	0	Sorghum silage acs used Season 3
X 22 =	315	315	Sorghum grazed acs used Season 5
X 23 =	0	0	Supplem't–lb cottons'd cake used Season 1
X 24 =	0	0	Supplem't–lb cottons'd cake used Season 2
X 25 =	0	10574	Supplem't–lb cottons'd cake used Season 3
X 26 =	0	0	Supplem't–lb cottons'd cake used Season 4
X 27 =	0	0	Supplem't–lb cottons'd cake used Season 5
X 28 =	0	0	Supplem't–lb mineral block used Season 1
X 29 =	0	0	Supplem't–lb mineral block used Season 2
X 30 =	0	0	Supplem't–lb mineral block used Season 3
X 31 =	0	0	Supplem't–lb mineral block used Season 4
X 32 =	0	0	Supplem't–lb mineral block used Season 5
X 33 =	0	0	Supplem't–lb corn used Season 1
X 34 =	0	0	Supplem't–lb corn used Season 2
X 35 =	0	0	Supplem't–lb corn used Season 3
X 36 =	0	0	Supplem't–lb corn used Season 4
X 37 =	0	0	Supplem't–lb corn used Season 5
X 38 =	0	0	Supplem't–lb wheat used Season 1
X 39 =	0	0	Supplem't–lb wheat used Season 2
X 40 =	0	40000	Supplem't–lb wheat used Season 3
X 41 =	0	0	Supplem't–lb wheat used Season 4
X 42 =	0	0	Supplem't–lb wheat used Season 5
X 43 =	0	0	Supplem't–lb beet pulp used Season 1
X 44 =	0	0	Supplem't–lb beet pulp used Season 2
X 45 =	0	0	Supplem't–lb beet pulp used Season 3
X 46 =	0	0	Supplem't–lb beet pulp used Season 4
X 47 =	0	0	Supplem't–lb beet pulp used Season 5
X 48 =	0	0	No. cow-calf units grazed Seasons 1-5
X 49 =	0	0	No. steers grazed Seasons 1-5
X 50 =	832	817	No. steers grazed Season 5
X 51 =	0	0	No. steers grazed Seasons 1-4
X 52 =	694	744	No. steers grazed Seasons 1-3
X 53 =	0	0	Unused acs deep sand
X 54 =	0	0	Unused acs sandy plains
X 55 =	0	0	Unused acs loamy plains
X 56 =	0	0	Unused acs alfalfa
X 57 =	0	0	Unused acs sorghum
X 58 =	0	29426	Unused lb cottons'd cake supplem't
X 59 =	0	40000	Unused lb mineral block supplem't
X 60 =	0	40000	Unused lb corn supplem't
X 61 =	0	0	Unused lb wheat supplem't
X 62 =	0	40000	Unused lb beet pulp supplem't
X 63 =	29	5	Excess lb phosphorus Season 1
X 64 =	827	886	Excess lb phosphorus Season 2
X 65 =	524	580	Excess lb phosphorus Season 3
X 66 =	0	0	Excess lb phosphorus Season 4
X 67 =	361	365	Excess lb phosphorus Season 5
X 68 =	32459	32980	Excess lb protein Season 1
X 69 =	31488	33737	Excess lb protein Season 2
X 70 =	0	0	Excess lb protein Season 3
X 71 =	0	0	Excess lb protein Season 4
X 72 =	0	0	Excess lb protein Season 5
X 73 =	0	0	Excess lb dry matter Season 1
X 74 =	0	0	Excess lb dry matter Season 2
X 75 =	72288	0	Excess lb dry matter Season 3
X 76 =	0	0	Excess lb dry matter Season 4
X 77 =	0	0	Excess lb dry matter Season 5
X 78 =	0	0	No. cow-calf units > 0 grazed Seasons 1-5
X 79 =	0	0	No. steers > 0 grazed Seasons 1-5
X 80 =	832	817	No. steers > 0 grazed Season 5
X 81 =	0	0	No. steers > 0 grazed Seasons 1-4
X 82 =	694	744	No. steers > 0 grazed Seasons 1-3

[1] Contribution margin (or maximum objective) = \$92,003 for Solution 1 and \$92,781 for Solution 2.

period the steers would be sold. The calculated contribution margin for Plan II would be \$92,781. Again, adjusting for \$31,505 of fixed costs, the net profit would be \$61,276.

Discussion

Based on the assumption of known information, two possible management plans were determined for the Eastern Colorado Range Station (ECRS). In Plan I, when no supplemental feeds were used, net revenue was \$60,498. Making use of supplemental feeds in Plan II resulted in net revenue of \$61,276. Based on the objective of profit maximization, Plan II is the optimal management plan with an additional net revenue of \$778.

Dollarwise the advantage of using Plan II is very slight. Therefore, the land manager must examine further the effect of using supplemental feeds with respect to re-allocation of land use over the various seasons. The effect of re-allocation should be observed over a time period greater than one growing season. Including the element of time into the analysis will require modifications of the model developed in this study.

We have attempted to show from our analysis of the ECRS that the linear programming model is capable of assisting in the managing resource systems for market goods that include supply and demand components. If the management model is allowed to select production of those products that will maximize net revenues, it is unlikely that nonmarket items such as recreation and scenic beauty, that do not command a competitive market price, will be selected as part of the optimum product mix. The management model, however, may be used to determine opportunity cost of supplying a required quantity of nonmarket items. By using the management model in this manner, the resource manager would be able to determine the cost of supplying nonmarket items that may be a necessary part of the allocation of resource systems.

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