# OPTIMAL USE OF WATER AND RELATED RESOURCES FOR DIVERSIFIED AGRICULTURE ON OAHU, HAWAII: A HYPOTHETICAL STUDY

by

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AREAS ON THE ISLAND OF OAHU, HAWAII

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## ABSTRACT

*The study problem of diversified farming presented in this report represents one of the many hypothetical alternatives in anticipation of the possible future changes in agriculture patterns and land use on Oahu. Urbanization problems involved in the land use changes from agriculture into urban were not a part of the scope of this study.*

*The two major objectives of this study were: (1) to formulate an objective function and its constraints for the variables involved in diversified farming in the southwest region of Oahu, and (2) to show that the objective function and its constraints can be solved by the technique of linear programming.*

*Using the population projection for Oahu, 1970-2020, made by the Board of Water Supply, City and County of Honolulu, projections on available farm land, water, labor, and crops were made and benefit-cost analyses for diversified crops were performed for the study area. Once the coefficients and the limitations of the objective and the constraint functions were determined, the study problem was solved by the linear programming method. The computer program for the linear programming solutions was written in detail in Fortran IV language.*

*Results of this study indicated that (1) diversified farming in the study area should generate profits from selected vegetable crops for which local demand exists, and (2) the linear programming technique can be applied to obtain optimal solutions for problems involved in diversified farming.*

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# INTRODUCTION

As commented by Laas and Beicos (1967), the water supply system is by far the biggest industry because the tonnage produced by water supply systems all over the U.S.A. amounts to seven times that of all other industries put together. For Oahu alone as published in the *2020 plan* by the Board of Water Supply (BWS), City and County of Honolulu (C&C) (1971), the total average draft on the groundwater in 1970 was about 430 million gallons per day (mgd). Of the 430 mgd, 110 mgd was for urban water supply, 260 mgd was for sugarcane plantations, and 60 mgd was for other uses. While the developable natural replenishment of the groundwater is estimated to be about 560 mgd, the projected demand for urban water supply in the year 2020 is estimated to be 253 mgd. If the demand for water by sugarcane plantations and by other users remains constant, the groundwater resources would be sufficient to satisfy the total urban water demand over the next 50 years. On the other hand, as indicated in the *2020 plan*, if a reduction of irrigated sugarcane acreage occurs over the next 30 years, some 50 mgd of the irrigation water would be available for urban water and/or other agricultural uses. Thus with this possible change in land use, an opportunity to examine the possible optimal use of water and other resources in diversified farming for a selected area on Oahu is presented. Since problems involved in the change from agricultural into urban land use are very complex and are beyond the resources and time limit provided for this research project, the study objectives were confined mainly to the problems involved in diversified farming.

All the pertinent input data for the diversified farming systems analysis are stochastic in nature and therefore are unavailable. In order to alleviate this problem, recorded data were extrapolated to provide data for the future based upon population projections and the possible change in land use from 1970 to 2020 as estimated in the Board of Water Supply's *2020 plan*. Thus, the methodology presented in this report may be regarded as a tool for obtaining optimal solutions for diversified farming, and the sample study presented herein should be regarded as a hypothetical study to show the application of system analysis.

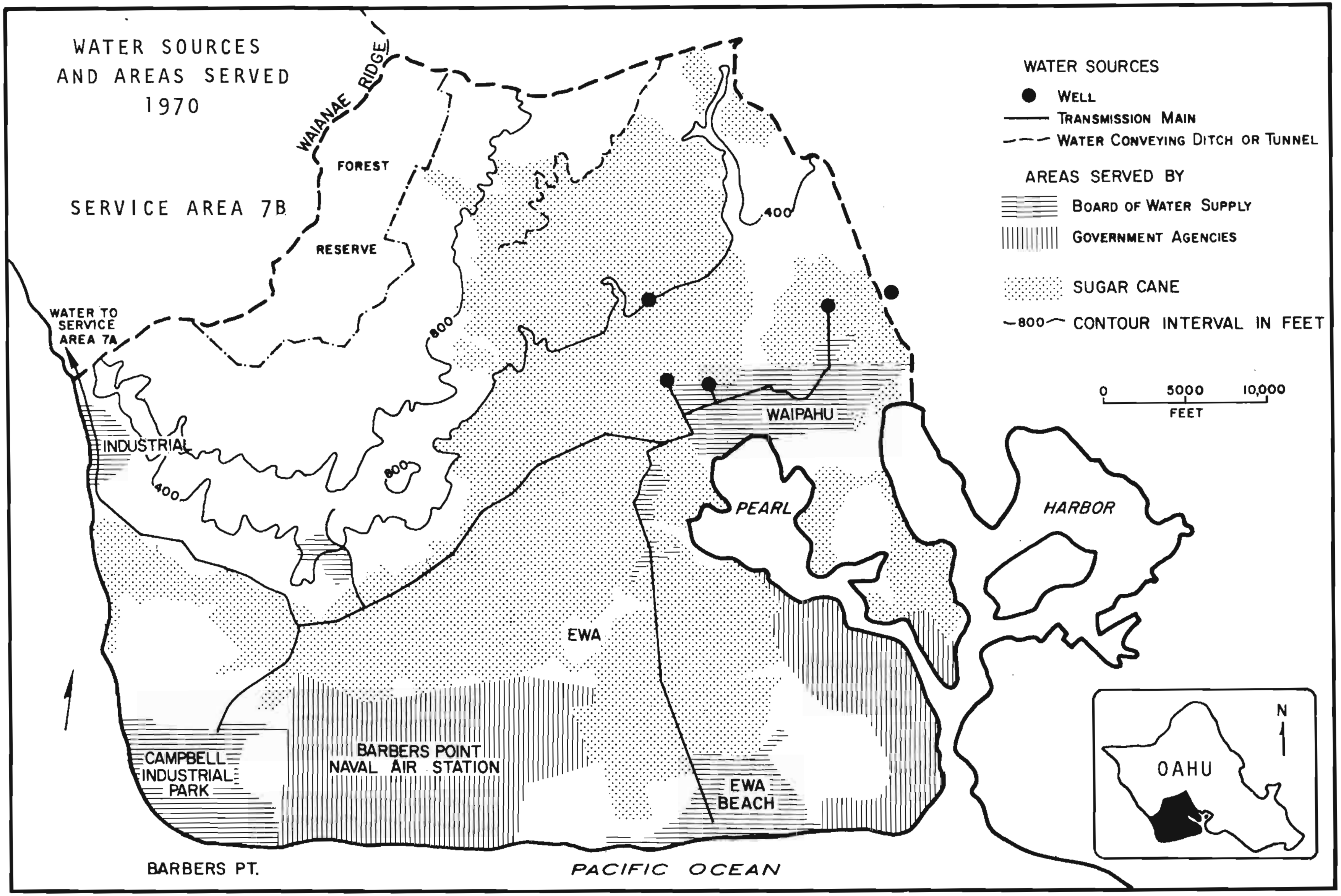
## BACKGROUND

During 1971 to 1973, the island of Oahu experienced a tremendous expansion in urban development, unparalleled in Hawaii's history. And there was rather strong sentiment expressed converting marginal agricultural land into urban uses. The southwest quadrant of Oahu, the area designated as Service Area 7-B in the *2020 plan* published by the Board of Water Supply, was once considered as one of the areas that could possibly be used to satisfy the demand for partial urban uses or diversified farming. Although subsequent economic conditions in the last couple of years have not favored such changes in land use, the potentials of diversified farming in the context of water and related resources warrant this study.

## DESCRIPTION OF THE STUDY AREA

With general reference to Visher and Mink (1964) and Dale (1967), and as described in the *2020 plan*, the area designated as Service Area 7-B shown in Figure 1 was selected as the study area. The *2020 plan* study area is located in the southwest section of Oahu and consists of 196.84 km$^2$ (76 mile$^2$). Except for the southern slopes of the Waianae Range which extend into the area, much of the land is gently sloping or nearly level. In 1970, it was estimated that more than 44% of the study area was planted in sugarcane. The major concentrations of population were located at Waipahu, Ewa, Ewa Beach, and Makakilo City and a portion of the area is used for military purposes (Barbers Point Naval Air Station and Puuloa Naval Reservation). The southwest corner of the area has been developed as the Campbell Industrial Park which includes two petroleum refineries, a cement plant, and a small steel mill. The de facto civilian population of this Service Area as of 1 April 1970 was estimated to be 47,300. During the preceding 10-yr period, growth was particularly rapid, averaging 7.4% increase per annum, and much of this rapid growth was the result of residential development in the Waipahu area.

Because of its productive soils and its topography, this area may continue as one of the major agricultural regions on Oahu. However, because of its proximity to Honolulu and its nucleus of heavy industries, this area could also expand into a residential and industrial center of Oahu. Therefore, according to the *2020 plan* (1971), residential development in this region is




SOURCE: Board of Water Supply, City and County of Honolulu. 1971. *2020 plan.*

FIGURE 1. LAND USE IN SOUTHWEST OAHU, 1970

expected to continue. The population projection, based upon an anticipated growth rate of 4.0% per year, gradually declining to 1.4% per year by the year 2020, will be 149,000. Major land uses for this region in 1970 are summarized in Table 1.

TABLE 1. MAJOR LAND USE IN SOUTHWESTERN OAHU, 1970

| Land Use | Acres |
|---|---|
| Sugarcane | 21,600 |
| Pineapple | 2,205 |
| Forest Reserve | 2,552 |
| Forest, Gulches | 7,940 |
| Military | 8,605 |
| Urban | 3,564 |
| Other (parks, croplands, 3300 acres [Pearl Harbor] and grazing) | 4,526 |
| Total | 50,992 |

SOURCE: *2020 plan* (1971).

## FORMULATION OF THE OBJECTIVE FUNCTION

There are many problems related to the change in land use, such as the reallocation of water resources, the subsequent development of urban areas and diversification of crops. In order to simplify the potential application of the system analysis presentation, the scope of this study was limited to diversified farming. Benefit and cost analyses of urban development from sugarcane land is purposely excluded because this is beyond the scope of this study, even though it is widely known that the land value will increase when land is rezoned for urban uses.

Since diversified farming aims at producing crops that will meet local demand at a cost compatible with shipments from the mainland U.S., the first phase analysis is to study the market demand for different crops, and to make the necessary projections using available data. Because market demand is more or less dependent on population, the projection of population growth in Oahu is therefore very important.

According to the *2020 plan* published in 1971 by the BWS, the population in Oahu was estimated to be 580,361 in 1970 and projected to be 1,500,000 in 2020 following a linear growth rate of 18,393 per year, or about 3.17% per year.

The hypothetical reduction of sugarcane land for urban use in the study area was calculated by using a linear reduction rate of 600 acres for every 5 years starting from 21,600 acres in 1970. At the same time some of the sugarcane land will be used for diversified farming. According to the *Statistics of Hawaiian agriculture* (1975), lettuce and potato top the list of produce shipped from the mainland U.S., and both crops have been proven profitable for local production. Therefore, both crops were selected for the diversified farming study in this project.

## Development of Income Functions for Selected Crops

The four selected diversified crops for this study are lettuce, potato, pineapple, and sugarcane. Production data for lettuce and potatoes were obtained from *Statistics of Hawaiian agriculture* (1975) as shown in Table 2. In this table, the Acreage Needed column was computed from inshipment/(yield per crop per acre x no. of crops per year). Data for sugarcane (Table 3) were also obtained from this statistic as data for pineapple (Table 4) were obtained from the *Pineapple fact book* (1972). The price per pound and the per acre yield per year data for lettuce and potato were plotted against the respective year from 1950 to 1974 and the projections of the future price and yield from 1975 to 2020 were made by extrapolating past trends with population projections as shown in Figures 2 and 3.

Similarly, the per ton price of sugarcane and the projections of the future price are shown in Figure 4. And the same analyses for pineapple are shown in Figure 5.

Finally, the annual per acre income for each crop for the period 1970 to 2020 (in 5-yr increments) were obtained from the respective Figures 2, 3, 4, and 5 and have been tabulated respectively in column 2 as shown in Tables 5, 6, and 7, and in column 3 Table 8 for lettuce, potatoes, pineapple, and sugarcane. For example, the annual per acre income of lettuce for 1975 was computed to be $12,110 per acre per year, which is the product of per pound price at 22.8¢/pound (from Fig. 2) and the yield of 17,700 pound per crop (from Fig. 3) with 3 crops per year.

In actuality, the income functions should be obtained by stochastic

TABLE 2. STATISTICAL DATA FOR LETTUCE AND POTATO PRODUCTION

| Year | Lettuce | | | | Potato | | | |
|---|---|---|---|---|---|---|---|---|
| | Oahu Price ¢/lb | Yield 1000 lb/ac | Inshipment 1000 lbs | Land Needed Acres | State Price ¢/lb | Yield 1000 lb/ac | Inshipment 1000 lbs | Land Needed Acres |
| 1949 | 13.0 | 13.3 | 653 | 16 | 8.0 | 5.5 | 16,436 | 996 |
| 1950 | 13.2 | 12.5 | 1,389 | 37 | 7.0 | 5.7 | 17,266 | 1,010 |
| 1951 | 12.2 | 11.7 | 1,825 | 52 | -- | 5.0 | 20,376 | 1,358 |
| 1952 | 12.6 | 13.8 | 1,285 | 31 | 8.8 | 5.5 | 16,586 | 1,005 |
| 1953 | 12.2 | 14.0 | 1,737 | 41 | 9.5 | 5.0 | 21,895 | 1,460 |
| 1954 | 13.0 | 13.9 | 2,108 | 51 | 5.7 | 5.9 | 23,941 | 1,353 |
| 1955 | 11.7 | 16.6 | 1,799 | 36 | 7.2 | 6.5 | 23,792 | 1,220 |
| 1956 | 13.6 | 11.2 | 3,170 | 94 | 7.1 | 6.0 | 24,654 | 1,370 |
| 1957 | 12.7 | 11.0 | 3,444 | 104 | 6.7 | 6.5 | 26,515 | 1,360 |
| 1958 | 12.1 | 13.6 | 3,166 | 78 | 9.3 | 8.0 | 29,329 | 1,222 |
| 1959 | 13.3 | 12.9 | 3,411 | 88 | 8.5 | 7.0 | 25,895 | 1,233 |
| 1960 | 10.3 | 15.0 | 3,127 | 69 | 7.7 | 7.0 | 25,004 | 1,191 |
| 1961 | 11.9 | 13.5 | 3,474 | 86 | 7.8 | 6.8 | 25,945 | 1,272 |
| 1962 | 12.2 | 16.7 | 3,481 | 69 | 7.5 | 5.6 | 24,815 | 1,477 |
| 1963 | 14.2 | 13.0 | 4,173 | 107 | 7.9 | 6.0 | 27,804 | 1,545 |
| 1964 | 13.5 | 14.7 | 4,243 | 96 | 7.9 | 7.2 | 29,823 | 1,381 |
| 1965 | 14.0 | 14.0 | 4,736 | 113 | 9.8 | 6.7 | 26,919 | 1,339 |
| 1966 | 14.0 | 14.1 | 4,007 | 95 | 8.3 | 10.4 | 28,838 | 924 |
| 1967 | 13.7 | 16.5 | 5,657 | 114 | 5.3 | 11.2 | 34,215 | 1,000 |
| 1968 | 16.7 | 15.2 | 6,852 | 150 | 5.8 | 6.7 | 31,934 | 1,589 |
| 1969 | 16.2 | 14.9 | 7,110 | 159 | 10.7 | 11.0 | 30,121 | 913 |
| 1970 | 19.9 | 16.4 | 7,637 | 155 | 6.9 | 6.7 | 33,152 | 1,649 |
| 1971 | 17.8 | 15.3 | 9,303 | 203 | 5.9 | 10.4 | 28,764 | 922 |
| 1972 | 19.5 | 15.5 | 9,292 | 200 | 6.9 | 10.7 | 27,163 | 846 |
| 1973 | 19.5 | 19.0 | 9,586 | 168 | 5.8 | 16.1 | 27,039 | 567 |
| 1974 | 21.9 | 16.4 | 10,366 | 211 | 6.4 | 17.2 | 25,989 | 548 |
| 1975 | 24.6 | 16.1 | 10,197 | -- | -- | -- | 25,714 | -- |

SOURCE: *Statistics of Hawaiian agriculture, 1975*, Department of Agriculture, State of Hawaii.

TABLE 3. PRICE FOR SUGARCANE IN OAHU

| Year | $/ton | Year | $/ton |
|---|---|---|---|
| 1960 | 9.3 | 1968 | 10.7 |
| 1961 | 9.0 | 1969 | 11.3 |
| 1962 | 9.5 | 1970 | 12.3 |
| 1963 | 12.3 | 1971 | 11.8 |
| 1964 | 9.7 | 1972 | 13.1 |
| 1965 | 9.8 | 1973 | 16.2 |
| 1966 | 10.7 | 1974 | 50.1 |
| 1967 | 10.6 | | |

SOURCE: *Statistics of Hawaiian agriculture* (1975), Department of Agriculture, State of Hawaii.

TABLE 4. STATISTICAL DATA FOR PINEAPPLE PRODUCTION

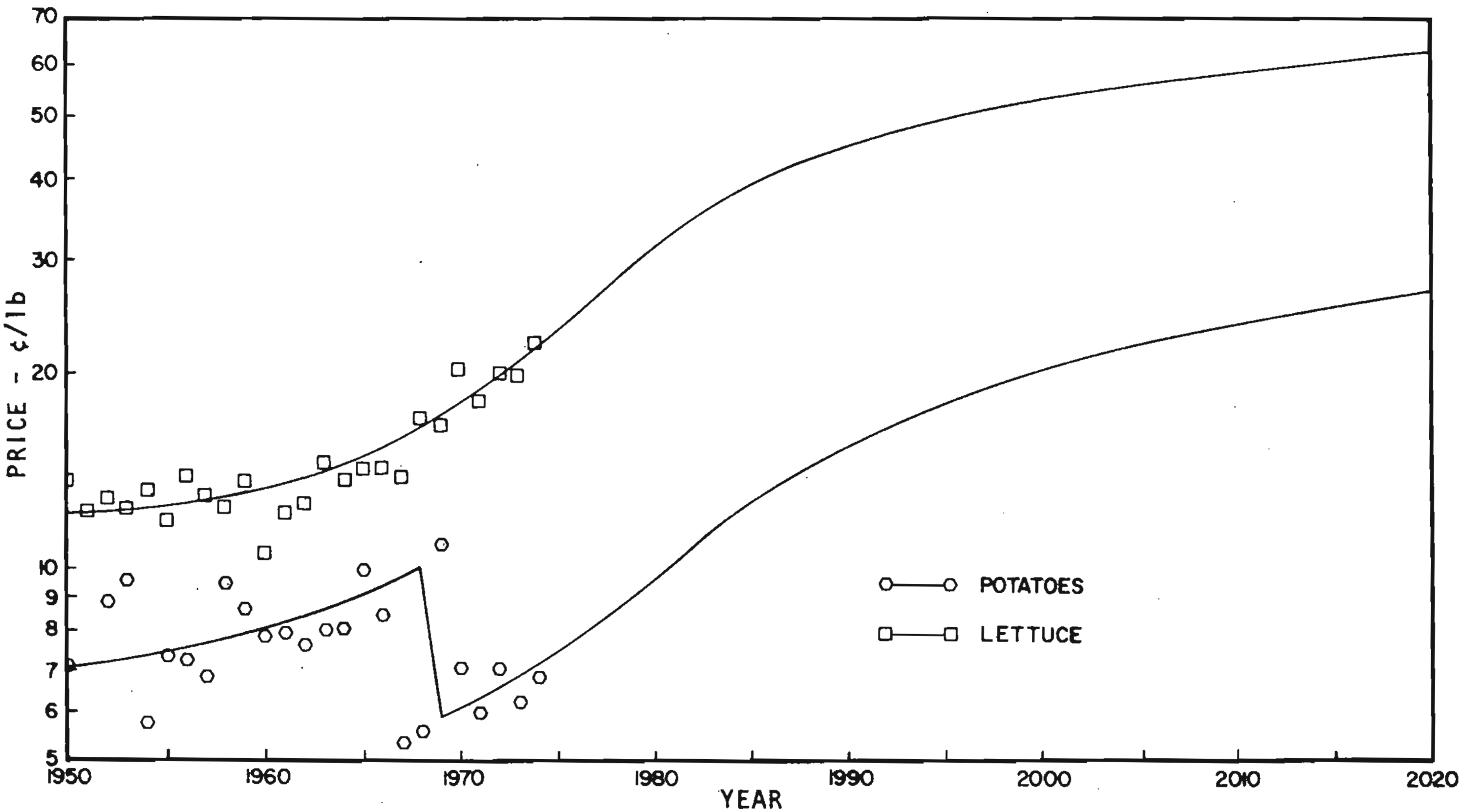
| Year | Pineapple Income | Cost | Profit |
|---|---|---|---|
| | --------------$ per acre-------------- | | |
| 1962 | 1620 | 1205 | 415 |
| 1964 | 1810 | 1282 | 528 |
| 1966 | 1879 | 1264 | 615 |
| 1968 | 1935 | 1330 | 605 |
| 1971 | 2203 | 1622 | 581 |

SOURCE: *Pineapple fact book* (1972), Pineapple Research Institute Honolulu, Hawaii.

analysis, however, stochastic analysis is expected to be very complex, therefore simple extrapolations of income functions have been applied in this hypothetical study.

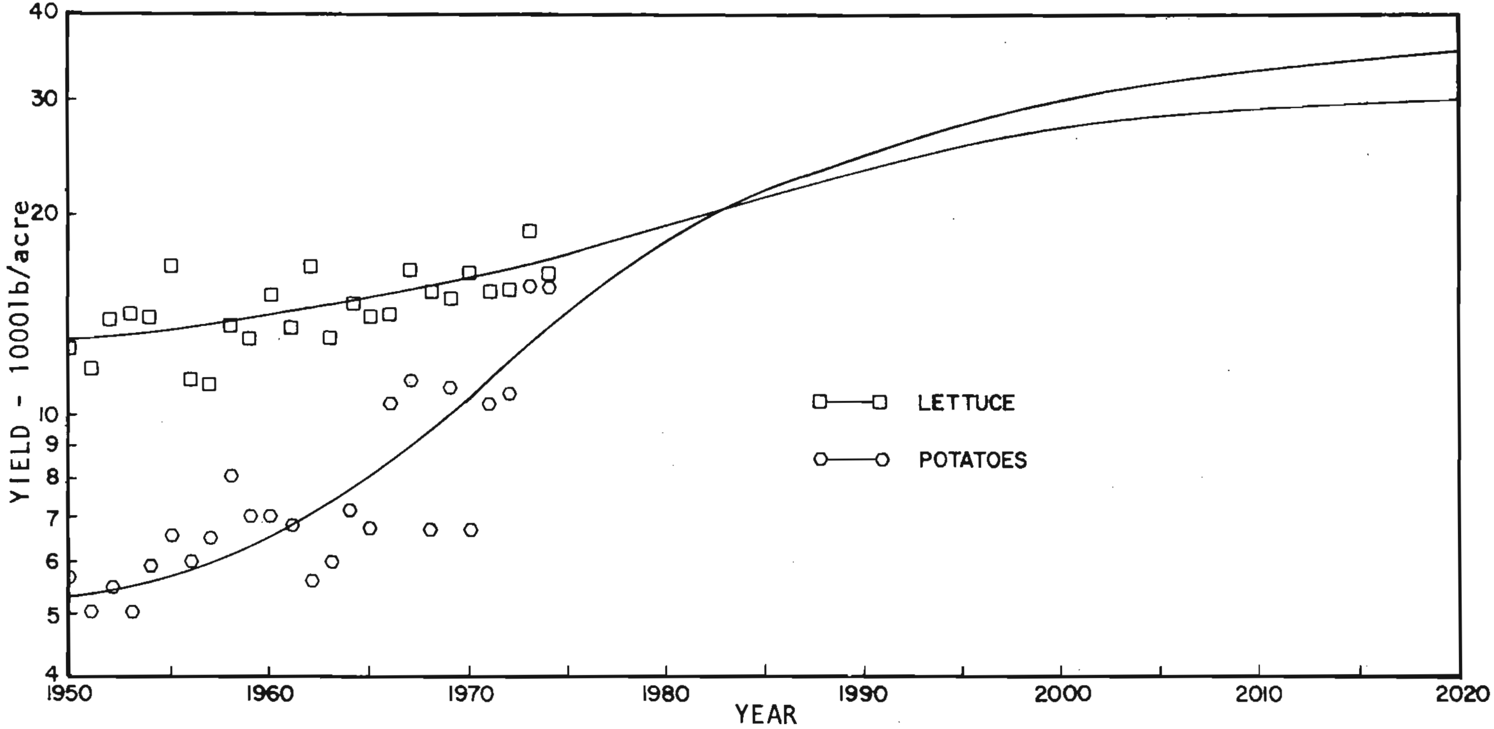
## Development of Cost Functions for Selected Crops

Since the production costs for lettuce, potatoes, and sugarcane can only be evaluated for 1970 or earlier years, the production cost for the 1975 to 2020 period must be projected. It is assumed that the production cost will probably be some percentage of the incremental income, the income is defined as the product of the annual per acre crop yield and the crop price per unit weight for a given year. Both the annual per acre crop yield



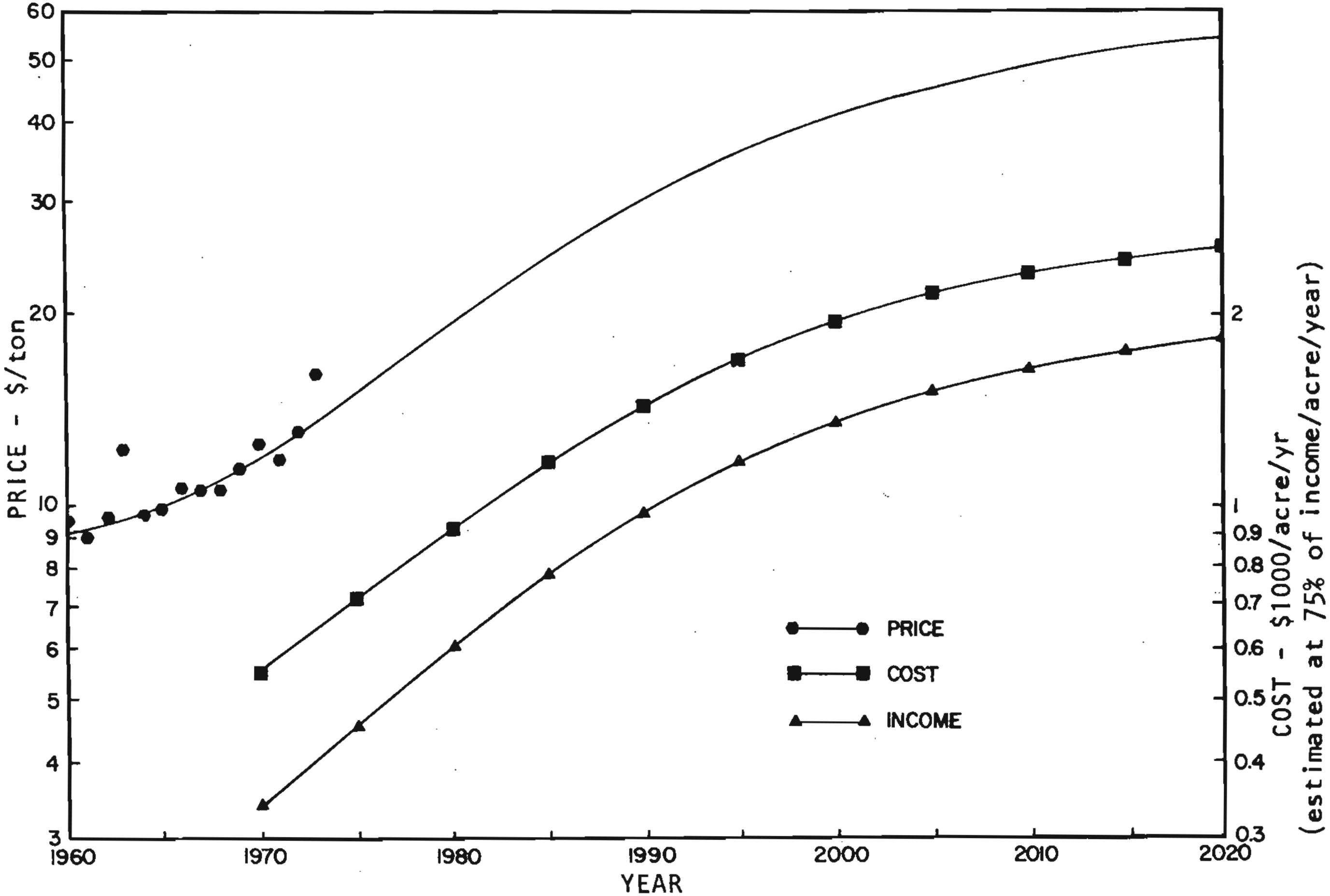

NOTE: 1950-1974 data from *Statistics of Hawaiian Agriculture*, Department of Agriculture, Hawaii.

FIGURE 2. PRICE PROJECTION FOR LETTUCE AND POTATOES IN OAHU, 1975-2020



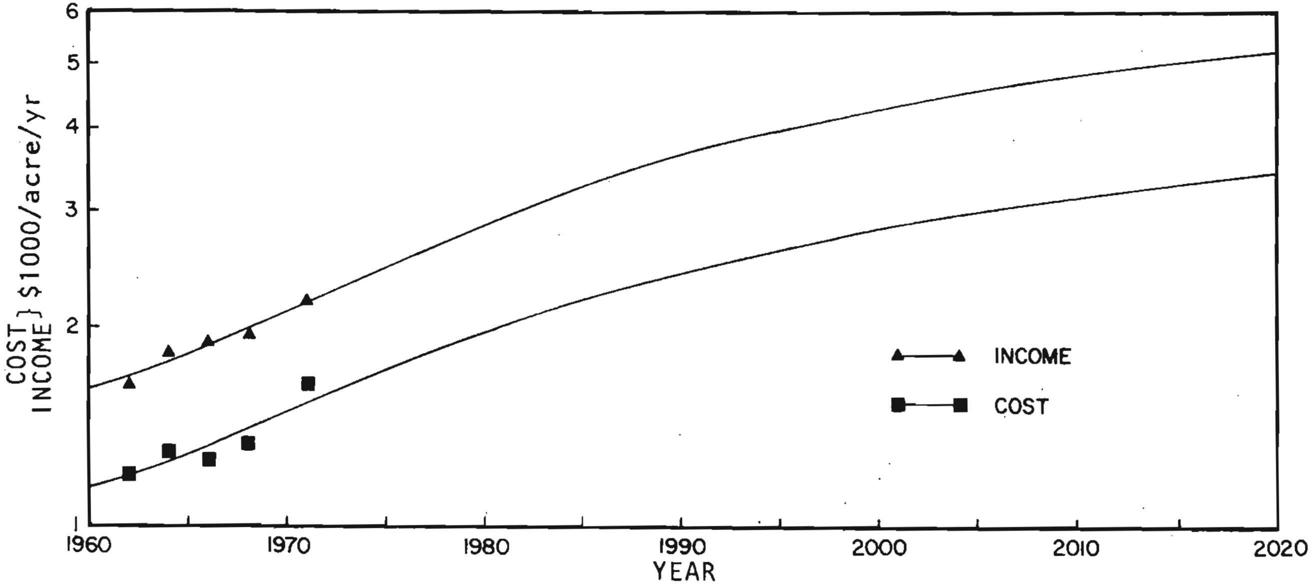

NOTE: 1950-1974 data from *Statistics of Hawaiian Agriculture*, Department of Agriculture, Hawaii.

FIGURE 3. YIELD PROJECTION FOR LETTUCE AND POTATOES IN OAHU, 1975-2020




NOTE: 1960-1974 data from *Statistics of Hawaiian Agriculture*, Department of Agriculture, Hawaii

FIGURE 4. PRICE, INCOME, AND COST PROJECTIONS FOR SUGARCANE IN OAHU, 1975-2020




NOTE: 1962-1971 data from *Pineapple Fact Book*, Pineapple Research Institute of Hawaii, Pineapple Growers Association of Hawaii.

FIGURE 5. PRICE, INCOME, AND COST PROJECTIONS FOR PINEAPPLE IN OAHU, 1975-2020

TABLE 5. PROJECTED PER ACRE INCOME, COST, PROFIT, AND ACREAGE FOR LETTUCE PRODUCTION, 1970-2020

Income = Yield x Price x no. of crops per year
Acreage Needed = Inshipment/(Yield x no. of crops)*

| Year | Income $/ac/yr | Cost $/ac/yr | Net Profit $/ac/yr | Acreage Needed |
|---|---|---|---|---|
| 1970 | 8,360 | 1,150** | 7,210 | 190 |
| 1975 | 12,110 | 3,960 | 8,150 | 200 |
| 1980 | 18,250 | 8,570 | 9,680 | 200 |
| 1985 | 24,950 | 13,590 | 11,360 | 190 |
| 1990 | 31,770 | 18,710 | 13,060 | 190 |
| 1995 | 37,920 | 23,320 | 14,600 | 190 |
| 2000 | 42,830 | 27,000 | 15,830 | 190 |
| 2005 | 47,290 | 30,350 | 16,940 | 200 |
| 2010 | 51,680 | 33,640 | 18,040 | 200 |
| 2015 | 55,270 | 36,330 | 18,940 | 200 |
| 2020 | 57,650 | 38,120 | 19,530 | 210 |

* Three crops per year.
**Cost projected from Mollet's (1961) data.

TABLE 6. PROJECTED PER ACRE INCOME, COST, PROFIT, AND ACREAGE FOR POTATO PRODUCTION, 1970-2020

Income = Yield x Price x no. of crops per year
Acreage Needed = Inshipment/(Yield x no. of crops)*

| Year | Income $/ac/yr | Cost $/ac/yr | Net Profit $/ac/yr | Acreage Needed |
|---|---|---|---|---|
| 1970 | 1,950 | 950** | 1,000 | 930 |
| 1975 | 3,140 | 2,020 | 1,120 | 780 |
| 1980 | 5,220 | 3,890 | 1,330 | 670 |
| 1985 | 8,020 | 6,410 | 1,610 | 610 |
| 1990 | 11,640 | 9,670 | 1,970 | 580 |
| 1995 | 14,950 | 12,650 | 2,300 | 550 |
| 2000 | 18,120 | 15,500 | 2,620 | 540 |
| 2005 | 21,160 | 18,240 | 2,920 | 540 |
| 2010 | 24,000 | 20,800 | 3,000 | 540 |
| 2015 | 26,500 | 23,040 | 3,460 | 560 |
| 2020 | 28,700 | 25,030 | 3,670 | 580 |

* Three crops per year.
**Estimated cost.

TABLE 7. PROJECTED PER ACRE INCOME, COST, PROFIT, AND ACREAGE FOR PINEAPPLE PRODUCTION, 1970-2020

| Year | Income* $/ac/yr | Cost $/ac/yr | Net Profit $/ac/yr |
|---|---|---|---|
| 1970 | 2,110 | 1,500 | 610 |
| 1975 | 2,470 | 1,730 | 740 |
| 1980 | 2,860 | 1,970 | 890 |
| 1985 | 3,270 | 2,200 | 1,070 |
| 1990 | 3,630 | 2,420 | 1,210 |
| 1995 | 3,990 | 2,630 | 1,360 |
| 2000 | 4,290 | 2,820 | 1,470 |
| 2005 | 4,550 | 3,000 | 1,550 |
| 2010 | 4,800 | 3,170 | 1,630 |
| 2015 | 5,050 | 3,300 | 1,750 |
| 2020 | 5,200 | 3,400 | 1,800 |

*Income = yield x price x no. of crops per year.

TABLE 8. PROJECTED PER ACRE INCOME, COST, PROFIT, AND ACREAGE FOR SUGARCANE PRODUCTION, 1970-2020

Income = Yield x Price x no. of crops per year
Yield = 94.3 tons/acre*, 0.5 crops per year

| Year | Price $/ton | Income $/acre/yr | Cost $/acre/yr | Net Profit $/acre/yr |
|---|---|---|---|---|
| 1970 | 11.8 | 556 | 337** | 219 |
| 1975 | 15.0 | 707 | 450 | 257 |
| 1980 | 19.4 | 915 | 606 | 309 |
| 1985 | 24.5 | 1,160 | 790 | 370 |
| 1990 | 30.2 | 1,420 | 980 | 440 |
| 1995 | 35.9 | 1,690 | 1,190 | 500 |
| 2000 | 41.1 | 1,940 | 1,380 | 560 |
| 2005 | 45.2 | 2,130 | 1,520 | 610 |
| 2010 | 48.5 | 2,290 | 1,640 | 650 |
| 2015 | 51.8 | 2,440 | 1,750 | 690 |
| 2020 | 54.3 | 2,560 | 1,840 | 720 |

* Averaged and assumed to be constant for 1970-2020.
**Estimated cost.

and the crop price per unit weight for lettuce and potatoes were projected for the 1975 to 2020 period as shown in Figures 2 and 3. The income for each crop was then computed and is shown respectively in column 2 of Tables 5 and 6. Income for pineapple and sugarcane was obtained directly from Figures 4 and 5 and is tabulated respectively in column 2 of Table 7 and in column 3 of Table 8.

The production costs for lettuce and sugarcane have been defined to be 75% of the incremental income plus the base year's cost, while the production cost for potatoes has been defined to be 90% of the incremental income plus the base year cost. The production cost of pineapple has been read directly from the cost curve in Figure 4 where the projected cost function was based upon available cost data from 1962 to 1971 as shown in column 3 of Tables 4 and 7.

For example, the production cost per acre of lettuce for 1975 was computed as: (\$12,110 - \$8,360) (0.75) + \$1,150 = \$3,960.

## Development of Net Profit Functions

The net annual profits for each crop per acre have been obtained by taking the difference between the annual income and the annual cost from Figures 2 to 6. The computed data have been tabulated respectively in column 4 of Tables 5, 6, and 7 for lettuce, potatoes, and pineapple and have been shown in column 5 of Table 8 for sugarcane.

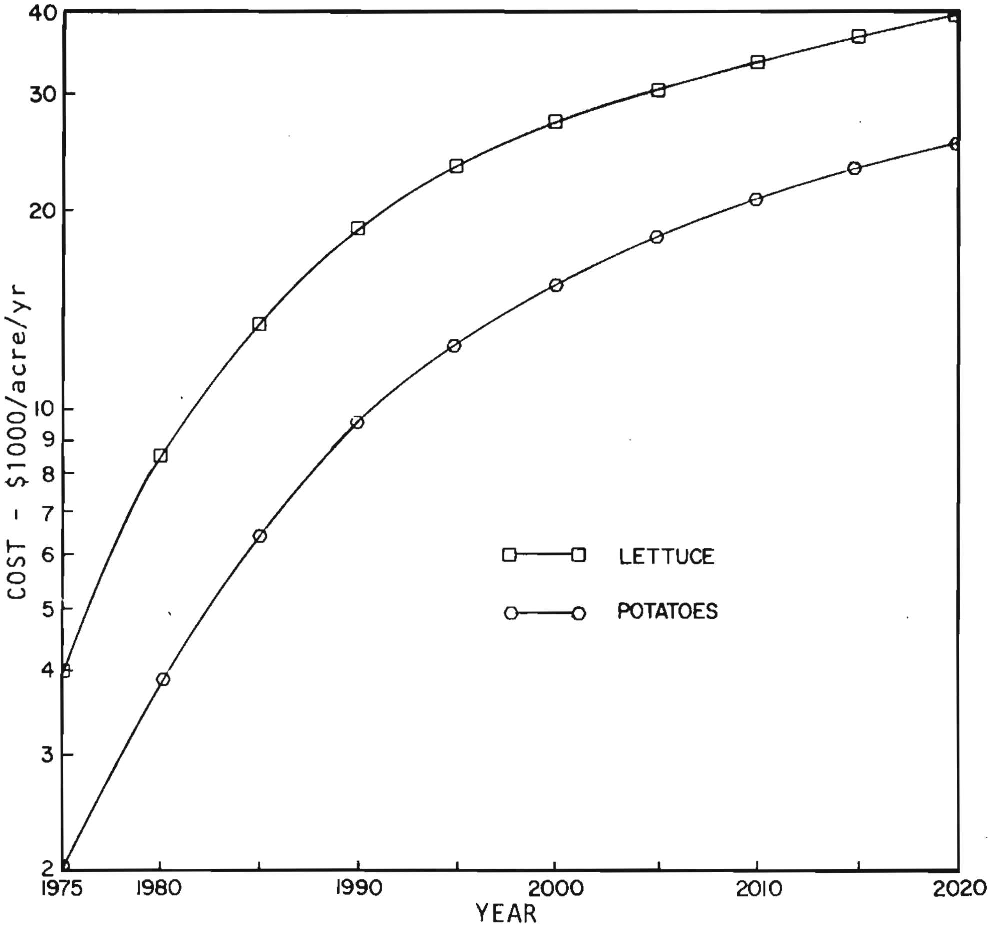
## Development of Constraints on Lettuce and Potato Acreages

The production of lettuce and potatoes is limited by the consumption capacity of the Oahu market as indicated by the yearly inshipment of each crop to Oahu in the *Statistics of Hawaiian agriculture*. The inshipment records may be regarded as the documented potentials for diversified farming. Therefore, the acreage of land needed for crops, such as lettuce and potatoes, can be computed by the following method:

$$\underset{\text{(acre)}}{\text{land needed for given crop}} = \underset{\text{(pounds)}}{\text{annual inshipment}} \Big/ \underset{\text{pounds per acre}}{\text{(crop yield)}}\ \text{(number of crops per year)}$$

Results of land needed for lettuce and potatoes have been tabulated respectively in column 5 of Tables 5 and 6.

In order to maintain a good supply-demand relationship to support a healthy diversified farming practice, the acreage for lettuce and potatoes




NOTE: Data were estimated; for lettuce cost was estimated as 75% of the income and for potato, cost was estimated as 90% of the income.

FIGURE 6. COST PROJECTIONS FOR LETTUCE AND POTATOES IN OAHU, 1975-2020

should not exceed the acreage needed to offset the inshipment of each crop. Therefore, the computed acreage needed for lettuce and potato may be regarded as the constraints for diversified farming.

### Formulation of the Objective Function

With the benefit-cost analysis performed for each crop as shown in Tables 5, 6, 7, and 8, the net profit columns of these Tables will provide the coefficients for the objective function for the select 5-yr periods. For example, for the year 1970, the objective function can be formulated as:

$$\text{Obj. Func. Max. } Z = 7210\ AL + 1000\ PO + 610\ PI + 219\ C \qquad (1)$$

in which Z = profit in dollars

AL = acreage for lettuce production

PO = acreage for potato production

PI = acreage for pineapple production

C = acreage for sugarcane production

## FORMULATION OF CONSTRAINT FUNCTIONS

In order to determine the maximum profit as described by the objective function in equation (1), the limitations of the resources of crop land, water, and labor involved in the evaluation of the coefficients in equation (1) should be defined both in time and in place. Sugarcane land available for diversified farming is estimated initially to be 21,600 acres reduced by 600 acres for every 5-yr period for urban development. Freshwater availability for irrigation is also estimated from the available sugarcane land at 4 acre-foot per acre per year. This figure is less than the optimal requirement for sugarcane production due to the lack of irrigation water. Labor availability is estimated at 0.055 person per acre for all land under cultivation. According to a marketing analysis, land for lettuce is limited to 190 acres and for potato to 930 acres in this study.

Data related to resources required for crop production per acre are estimated and presented in Table 9.

According to information found and those listed in Table 9, the constraint equations are formulated in the following:

$$\text{Limitation For Land: } AL + PO + PI + C \leq AGLI \qquad (2)$$

$$\text{Limitation For Water: } 4.02\ AL + 3.35\ PO + 1.12\ PI + 5.0\ C \leq AGLI \qquad (3)$$

TABLE 9. RESOURCES REQUIRED FOR PER ACRE CROP PRODUCTIONS, 1973 TO 1974

| Crop | Water Needed/Day in 1000 gallons | Labor Needed Persons Per Acre |
|---|---|---|
| Lettuce | 4.02 | 0.500 |
| Potato | 3.35 | 0.210 |
| Pineapple | 1.12 | 0.119 |
| Sugarcane | 5.00 | 0.041 |

Limitation For Labor: $0.5\ AL + 0.21\ PO + 0.119\ PI + 0.041\ C \leq 0.055\ AGLI$ (4)
Limitation For Lettuce: $AL \leq 190$ (5)
Limitation For Potatoes: $PO \leq 930$ (6)
in which AGLI = agricultural land available for diversified farming in acres for a given period, AL, PO, PI and C are the four crops' farming area defined previously. Equation (2) indicates that the farming areas of the four diversified crops cannot exceed the total area available for agriculture for a given period. All the coefficients in equations (2) to (6) are estimated in a deterministic manner based on 1973-74 conditions.

## METHOD TO OBTAIN THE OPTIMAL SOLUTIONS

Equations (2) to (6) represent a set of simultaneous linear equations which can be solved by many methods. Some of these methods are designed for manual solutions and some are developed for computer process.

In order to demonstrate how the solutions for the linear programming model are obtained, an example of a numerical solution of the problem stated previously by equations (1) to (6) for the 1970-1974 period is given in Appendix A using the modified simplex method "Tucker's Tableau" for computation. The results can be used as a check of computer computations of the same period which is provided in the computer printout in Appendix E.

The manual solution of the linear programming is time consuming, and the procedures of solution for linear programming can be adopted easily by a computer program in a sub-routine. A diversified farming program for southwestern Oahu has been prepared under a main computer program using Fortran IV statements. This computer program can be readily adopted for additional variables and constraints in order that this method can be used by the potential users. The computer input format is presented in Appendix B, the card deck arrangement is shown in Appendix C; the main and subroutine (LPGO) flow charts are included in Appendix D. Finally, the printouts of the main and subroutine (LPGO) programs have been documented with definitions of variables, programs, tabulations of the input data, and optimal solutions for the 1970-2020 period for diversified farming in southwestern Oahu (App. E).

## RESULTS AND DISCUSSIONS

The results of this study are presented in the last part of the computer program print-out as shown in Appendix D, and are again summarized here in Table 10.

TABLE 10. OPTIMAL SOLUTIONS FOR DIVERSIFIED FARMING, 1970-2020

| Year | Optimal Maximum Profit, $ | Land Available Acres | Land Committed for Diversified Farming | | | |
|---|---|---|---|---|---|---|
| | | | Lettuce | Potato | Pineapple | Sugarcane |
| | | | Acres | | | |
| 1970 | 7,116,900 | 21,600 | 190 | 0 | 3,558 | 16,330 |
| 1975 | 8,222,930 | 21,000 | 200 | 0 | 3,394 | 15,878 |
| 1980 | 9,615,956 | 20,400 | 200 | 0 | 3,273 | 15,425 |
| 1985 | 11,116,178 | 19,800 | 190 | 0 | 3,194 | 14,971 |
| 1990 | 12,588,432 | 19,200 | 190 | 0 | 3,073 | 14,518 |
| 1995 | 13,821,789 | 18,600 | 190 | 0 | 2,952 | 14,065 |
| 2000 | 14,797,659 | 18,000 | 190 | 540 | 1,933 | 13,452 |
| 2005 | 15,533,604 | 17,400 | 190 | 540 | 1,811 | 12,999 |
| 2010 | 16,178,735 | 16,800 | 200 | 540 | 1,648 | 12,548 |
| 2015 | 16,681,035 | 16,200 | 200 | 560 | 1,493 | 12,089 |
| 2020 | 16,938,724 | 15,600 | 210 | 580 | 1,296 | 11,632 |

According to the results presented above, one can observe that in order to obtain a maximum profit for the diversified farming of the four crops, some of the available land would be left un-utilized. This is due to the nature of the various constraints from the benefit and cost analysis, and due to the limitations on water, labor, and crops. Available but uncommitted agriculture land ranges from about 1400 to 1900 acres as shown in the following list:

| Year | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Acres | 1521 | 1527 | 1550 | 1443 | 1418 | 1392 | 1885 | 1858 | 1864 | 1858 | 1882 |

The reason that a sizable acreage of land will not be utilized for each study period is that potato farming is not recommended for the period 1970 to 1995 due to the low profit margin set for this crop. If the allowable profit for potato farming is set at a higher level comparable to those set for lettuce, pineapple and sugarcane, the result of the optimization would show a higher percentage of land utilization. The other reason is due to constraints of this optimization model such as the availabilities of water and labor and the limitations on acreages of lettuce and potato for each study period.

In an actual application of the linear programming optimization technique for diversified farming and in order to obtain a complete land utilization, it is recommended that other crops be considered so that the land resources may be fully utilized for each study period.

As indicated in the earlier part of this study, diversified crops are not limited only to lettuce and potato. Demand for other produce, such as tomato, watermelon, and others do exist on Oahu. These potential crops may be added on to the study model without creating major changes in the mathematical formulation of the study model and in the computer programs when steps for benefit-cost analysis in this study are followed. A second recommendation is that a sensitivity study of the constraints upon the objective function or a sensitivity analysis of the whole system be performed which might lead to the full utilization of the land resources of the study area.

The importance of the benefit-cost analysis on the results obtained from this model is recognized in this study. If the benefit-cost analysis is representative, the results of system analysis would have to be reliable. The major problem encountered in this study was the lack of suitable data for the cost analysis. For example, the cost of producing lettuce in 1970 was estimated from an earlier study by Mollet (1961), and Mollet's data has been projected to suit 1970 conditions. Without this basic study of agricultural economics, it is very difficult to realistically estimate the production cost of lettuce. This difficulty was also encountered in estimating the cost of potato production. Since no official research report was found on this crop for Oahu, the estimation of potato production cost, which can be considered as reasonable, was based upon a newspaper article "Potatoes? He's Got 'Em" by Nadine Scott of the Honolulu Star Bulletin on 31 January 1974. In regard to the production cost for sugarcane, sufficient data were also not available because reported production costs were based upon unrefined sugar and molasses. Therefore, a separate estimation on sugarcane production cost had to be made based upon unpublished 1971 production data obtained from William S. Haines, Operation Manager of the Hawaiian Commercial and Sugar Company in Puunene, Maui. In addition, data reported in the USDA *Statistics of Hawaiian agriculture* can only be regarded as indices because vital factual data have been pooled for proprietary reasons.

## CONCLUSIONS

According to the study results obtained, the following concluding points can be made:

1. Diversified farming in southwestern Oahu should produce good profits from selected vegetable crops for which local demand exists.
2. The linear programming technique can be applied to determine the optimal solutions for allocating crop lands, water, and labor resources in supporting diversified farming operation.
3. The methodology for the application of linear programming to diversified farming has been presented in detail, especially the formulation of the objective and the constraint functions which can be readily adopted by potential users.
4. The importance of reliable input data to obtain representative income and cost functions for the systems analysis of diversified farming has been recognized. In order to obtain unbiased on-farm operational data, programs similar to the publication of the *Production cost notes* initiated by the Department of Agriculture and Resources Economics, University of Hawaii should be encouraged.

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# APPENDICES

## Appendix A. L.P. Problem - Variable Definitions

Let:

- AL ≡ acreage for lettuce
- PO ≡ acreage for potatoes
- PI ≡ acreage for pineapple
- C ≡ acreage for sugarcane
- Z ≡ profit in dollars per year

Initial conditions (1970):

AGLI ≡ 21,600 acres (land available)

4.0 • AGLI ≡ 86,400 acre-feet (water constraint)

0.055 • AGLI ≡ 1,188 man-year (labor constraint)

AL ≡ 190 acres (lettuce limitation)

PO ≡ 930 acres (potato limitation)

### Demonstration of Linear Programming Problem Solution

Obj. Func. Max Z = 7210 • AL + 1000 • PO + 610 • PI + 219 • C

Subject to:

| | | | | | |
|---|---|---|---|---|---|
| (ALAN) | AL + | PO + | PI + | C | $\leq$ AGLI |
| (WATR) | 4.02 • AL + | 3.35 • PO + | 1.12 • PI + | 5.00 • C | $\leq$ 4.0 AGLI |
| (ALBR) | 0.50 • AL + | 0.21 • PO + | 0.119 • PI + | 0.041 • C | $\leq$ 0.055 AGLI |
| (ALET) | AL | | | | $\leq$ 190 |
| (POTA) | | PO | | | $\leq$ 930 |

Introduce slack variables; X1, X2, X3, X4, and X5

| | | | | | |
|---|---|---|---|---|---|
| AL + | PO + | PI + | C + X1 | = | 21,600 |
| 4.02 AL + | 3.35 PO + | 1.12 PI + | 5.00 C + X2 | = | 86,400 |
| 0.05 AL + | 0.21 PO + | 0.119 PI + | 0.041 C + X3 | = | 1,188 |
| AL | | | + X4 | = | 190 |
| | PO | | + X5 | = | 930 |

Let X1, X2, X3, X4, and X5 be basic variables and AL, PO, PI, and C be nonbasic variables:

∴ (1a) Z = 0 + 7210 • AL + 1000 • PO + 610 • PI + 219 • C

(1b) X1 = 21600 + AL + PO + PI C

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (1c) | X2 = | 86400 + | 4.02 • | AL + | 3.55 • | PO + | 1.12 • | PI + | 5.00 • | C | |
| (1d) | X3 = | 1188 + | 0.50 • | AL + | 0.21 • | PO + | 0.119 • | PI + | 0.041 • | C | |
| (1e) | X4 = | 190 + | | AL | | | | | | | |
| (1f) | X5 = | 930 + | | | | PO | | | | | |

Tucker's Tableau I

| | | -AL | -PO | -PI | -C |
|---|---|---|---|---|---|
| Z | $y_{00} = 0$ | $y_{01} = -7210$ | $y_{02} = -1000$ | $y_{03} = -610$ | $y_{04} = -219$ |
| X1 | $y_{10} = 21600$ | 1 | 1 | 1 | 1 |
| X2 | $y_{20} = 86400$ | 4.02 | 3.35 | 1.12 | 5.00 |
| X3 | $y_{30} = 1188$ | 0.50 | 0.21 | 0.119 | 0.041 |
| X4 | $y_{40} = 190$ | 1 | 0 | 0 | 0 |
| X5 | $y_{50} = 930$ | 0 | 1 | 0 | 0 |

Optimality test fails because not all $y_{io}$ and $y_{oj}$ are nonnegative. Choose AL as the basic variable because it has the largest negative values of the nonbasic variables. Keep PO, PI, C as nonbasic variables, i.e., PO, PI, C = 0.

From: (1b) X1 = 21600 - AL ⇒ AL $\leq$ 21600 for X1 $\geq$ 0

(1c) X2 = 86400 - 4.02 • AL ⇒ AL $\leq$ 21493 for X2 $\geq$ 0

(1d) X3 = 1188 - 0.50 • AL ⇒ AL $\leq$ 2376 for X3 $\geq$ 0

(1e) X4 = 190 - AL ⇒ AL $\leq$ 190 for X4 $\geq$ 0

AL $\leq$ 190 controls. ∴ X4 becomes a nonbasic variable. Pivot about AL is equation (1e).

(2a) AL = 190 - X4 Substitute (2a) into the other equations.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| (2a)→(1a) | Z = | 1369900 - 7210 | X4 + 1000 | PO + 610 | | PI + 219 | | C | (2b) |
| (2a)→(1b) | X1 = | 21410 + | X4 - | PO - | | PI - | | C | (2c) |
| (2a)→(1c) | X2 = | 85636.2 + 4.02 • | X4 - 3.35 • | PO - 1.12 • | | PI - 5.00 • | | C | (2d) |
| (2a)→(1d) | X3 = | 1093 + 0.50 • | X4 - 0.21 • | PO - 0.119 • | | PI - 0.041 • | | C | (2e) |
| (2a) | AL = | 190 - X4 | | | | | | | |
| (2a)→(1f) | X5 = | 930 | - | PO | | | | | |

Tucker's Tableau II

| | | -X4 | -PO | -PI | -C |
|---|---|---|---|---|---|
| Z | 136900 | 7210 | -1000 | -619 | -219 |
| X1 | 21410 | -1 | 1 | 1 | 1 |
| X2 | 85636.2 | -4.02 | 3.35 | 1.12 | 5.00 |
| X3 | 1093 | -0.50 | 0.21 | 0.119 | 0.041 |
| AL | 190 | 1 | 0 | 0 | 0 |
| X5 | 930 | 0 | 1 | 0 | 0 |

Optimality test fails because not all $y_{io}$ and $y_{oj}$ are nonnegative. Choose PO as the basic variable because it has the largest negative value of the nonbasic variables.

Keep X4, PI, C as nonbasic variables, i.e., X4, PI, C = 0.

From:
(2c) $X1 = 21410 - PO \Rightarrow PO \le 21410$ for $X1 \ge 0$
(2d) $X2 = 85636.2 - 3.35 \cdot PO \Rightarrow PO \le 24468$ for $X2 \ge 0$
(2e) $X3 = 1093 - 0.21 \cdot PO \Rightarrow PO \le 5205$ for $X3 \ge 0$
(2f) $X5 = 930 - PO \Rightarrow PO \le 930$ for $X5 \ge 0$

$PO \le 930$ controls. $\therefore$ X5 becomes a nonbasic variable. Pivot about PO is equation (2f).

(3a) $PO = 930 - X5$ substitute (3a) into the other equations.

(3a) (2b) $X = 2299900 - 7210 \cdot X4 - 1000 \cdot X5 + 610 \cdot PI + 219 \cdot C$ (3b)
(3a) (2c) $X1 = 20480 + X4 + X5 - PI - C$ (3c)
(3a) (2d) $X2 = 82520.7 + 4.02 \cdot X4 + 3.35 \cdot X5 - 1.12 \cdot PI - 5.00 \cdot C$ (3d)
(3a) (2e) $X3 = 897.7 + 0.50 \cdot X4 + 0.21 \cdot X5 - 0.119 \cdot PI - 0.041 \cdot C$ (3e)
(3a) (2a) $AL = 190 - X4$ (3f)
(3a) $PO = 930 - X5$ (3a)

Tucker's Tableau III

| | | -X4 | -X5 | -PI | -C |
|---|---|---|---|---|---|
| Z | 2299900 | 7210 | 1000 | -610 | -219 |
| X1 | 20480 | -1 | -1 | 1 | 1 |
| X2 | 82520.7 | -4.02 | -3.35 | 1.12 | 5.00 |
| X3 | 897.7 | -0.50 | -0.21 | 0.119 | 0.041 |
| AL | 190 | 1 | 0 | 0 | 0 |
| PO | 930 | 0 | 1 | 0 | 0 |

Optimality test fails because not all $y_{io}$ and $y_{oj}$ are nonnegative. Choose PI as the basic variable because it has the largest negative value.

Keep X4, X5, C as nonbasic variable, i.e., X4, X5, C = 0.

From: (3c) X1 = 20480 - PI => PI $\leq$ 20480 for X1 $\geq$ 0

(3d) X2 = 92520.7 - 1.12 • PI => PI $\leq$ 73699 for X2 $\geq$ 0

(3e) X3 = 897.7 - 0.119 • PI => PI $\leq$ 7543.70 for X3 $\geq$ 0

PI 7543.70 controls. ∴ X3 becomes a nonbasic variable. Pivot about 0.119 PI is equation (3e).

0.119 PI = 897.7 + 0.50 • X4 + 0.21 • X5 - X3 - 0.041 • C

(4a) PI = 7543.70 + 4.202 • X4 + 1.765 • X5 - 8.403 • X3 - 0.345 • C

Substitute (4a) into the other equations.

(4a) (3b) Z = 6901555.46 - 4646.97 • X4 + 76.47 • X5 - 5126.05 • X3 + 8.83 • C (4b)

(4a) (3c) X1 = 12936.30 - 3.202 • X4 - 0.765 • X5 + 8.403 • X3 - 0.655 • C (4c)

(4a) (3d) X2 = 74071.76 - 0.686 • X4 + 1.374 • X5 + 9.412 • X3 - 4.614 • C (4d)

(4a) PI = 7543.70 + 4.202 • X4 + 1.765 • X5 - 8.403 • X3 - 0.345 • C (4a)

(4a) (3f) AL = 190 - X4 (4e)

(4a) (3a) PO = 930 - X5 (4f)

Tucker's Tableau IV

| | | -X4 | -X5 | -X3 | -C |
|---|---|---|---|---|---|
| Z | 6901555.46 | 4646.97 | -76.47 | 5126.05 | -8.83 |
| X1 | 12936.30 | 3.202 | 0.765 | -8.403 | 0.655 |
| X2 | 74071.76 | 0.686 | -1.374 | -9.412 | 4.614 |
| PI | 7543.70 | -4.202 | -1.765 | 8.403 | 0.345 |
| AL | 190 | 1 | 0 | 0 | 0 |
| PO | 930 | 0 | 1 | 0 | 0 |

Optimality test fails because not all $y_{io}$ and $y_{oj}$ are nonnegative. Choose X5 as the basic variable.

Keep X4, X3, C as nonbasic variables, i.e., X4, X3, C = 0.

From: (4c) X1 = 12936.30 - 0.765 • X5 => X5 $\leq$ 16190 for X1 $\geq$ 0
(4d) X2 = 74071.76 + 1.374 • X5 => X5 unbounded for X2 $\geq$ 0
(4e) PI = 7543.70 + 1.765 • X5 => X5 unbounded for PI $\geq$ 0
(4f) PO = 930 - X5 > X5 $\leq$ 930 for PO $\leq$ 0

X5 $\leq$ 930 controls. ∴ PO becomes a nonbasic variable. Pivot about X5 is equation (4f).

(5a) X5 = 930 - PO Substitute (5a) into the other equations.

(5a) (4b) Z = 69726.80 - 4646.97 • X4 - 76.47 • PO - 5126.05 • X3 + 8.83 • C (5b)

(5a) (4c) X1 = 12225.12 - 3.202 • X4 + 0.765 • PO + 8.403 • X3 - 4.614 • C (5c)

(5a) (4d) X2 = 75349.14 - 0.686 • X4 - 1.374 • PO + 0.412 • X3 - 0.655 • C (5d)

(5a) (4a) PI = 9184.88 + 4.202 • X4 - 1.765 • PO - 8.403 • X3 - 0.345 • C (5e)

(5a) X5 = 930 - PO (5a)

Tucker's Tableau V·

| | | -X4 | -PO | -X3 | -C |
|---|---|---|---|---|---|
| Z | 6972676.80 | 4646.97 | 76.47 | 5216.05 | -8.83 |
| X1 | 12225.12 | 3.202 | -0.765 | -8.403 | 0.655 |
| X2 | 76349.14 | 0.686 | 1.374 | -9.412 | 5.386 |
| PI | 9184.88 | -4.202 | 1.765 | 8.403 | 0.345 |
| AL | 190 | 1 | 0 | 0 | 0 |
| X5 | 930 | 0 | 1 | 0 | 0 |

Optimality test fails because not all $y_{io}$ and $y_{oj}$ are nonnegative. Choose C as the basic variable because it has the largest negative number.

Keep X4, PO, X3 as nonbasic variables, i.e., X4, PO, X3 = 0

From: (5c) X1 = 12225.12 - 0.655 • C => C $\leq$ 18665 for X1 $\geq$ 0

(5d) X2 = 75349.14 - 4.614 • C => C $\leq$ 16330.13 for X2 $\geq$ 0

(5e) PI = 9185.15 - 0.345 • C => C $\leq$ 26624 for PI $\geq$ 0

C $\leq$ 16330.13 controls. ∴ Let X2 become a nonbasic variable. Pivot about 4.614 C is (5d).

4.614 C = 75349.14 • X4 - 1.374 • PO + 8.403 • X3 - X2

(6a) C = 16330.13 - 0.1486.28 • X4 - 79.10 • PO - 5108.03 • X3 - 1.91 • X2

Substitue (6a) into the other equations.

(6a) (5b) Z = 7116900.49 - 4648.28 • X4 - 79.10 • PO - 5108.03 • X3 - 1.91 • X2 (6b)

(6a) (5c) X1 = 1521.34 - 3.1043 • X4 + 0.9599 • PO + 7.0663 • X3 + 0.1420 • X2 (6c)

(6a) C = 16330.13 - 0.1486 • X4 - 0.2978 • PO + 2.0398 • X3 - 0.2167 • X2 (6a)

(6c) (5c) PI = 3558.53 + 4.2429 • X4 - 1.8673 • PO - 9.1061 • X3 + 0.0747 • X2 (6d)

(6a) (5f) AL = 190 - X4 (6e)

(6a) (5a) X5 = 930 - PO (6f)

Tucker's Tableau VI

| | | -X4 | -PO | -X3 | -X2 |
|---|---|---|---|---|---|
| Z | 7116900.49 | 4648.28 | 79.10 | 5108.03 | 1.91 |
| X1 | 1521.34 | 3.1043 | -0.9599 | -7.0663 | -0.1420 |
| C | 16330.13 | 0.1486 | 0.2978 | -2.0398 | 0.2167 |
| PI | 3558.53 | -4.2529 | 1.8673 | 9.1061 | -0.0747 |
| AL | 190 | 1 | 0 | 0 | 0 |
| X5 | 930 | 0 | 1 | 0 | 0 |

*Optimality test passes.* (All $y_{io}$'s and $y_{oj}$'s are nonnegative.) X1, C, PI, AL, X5 are basic variables and X4, PO, X3, X2 are nonbasic variables, i.e., X4, PO, X3, X2 = 0.

*Optimal solution:*

AL = 190 acres (lettuce)
PO = 0 acres (potato)
PI = 3558.53 acres (pineapple)
C = 16330.13 acres (sugarcane)

Max. profit Z = $7,116,900.49 for the year 1970.

*Note:*

Due to the nature of the contraints, not all of the land available is utilized. In fact, 1,521.34 acres would not be used in 1970 to achieve an optimal return with respect to the constraints prescribed.

## Appendix B. Input Format

1. Title card. A title of any characters up to 80 can be punched on this card.
2. Control variable card.

    cols. 1-4, M, number of equations (slack variables).
    cols. 5-8, N, total number of variables (decision plus slack variables).
    cols. 9-12, II, number of decision variables.
    cols. 13-16, NS, number of sets of constraints and left hand side coefficients.

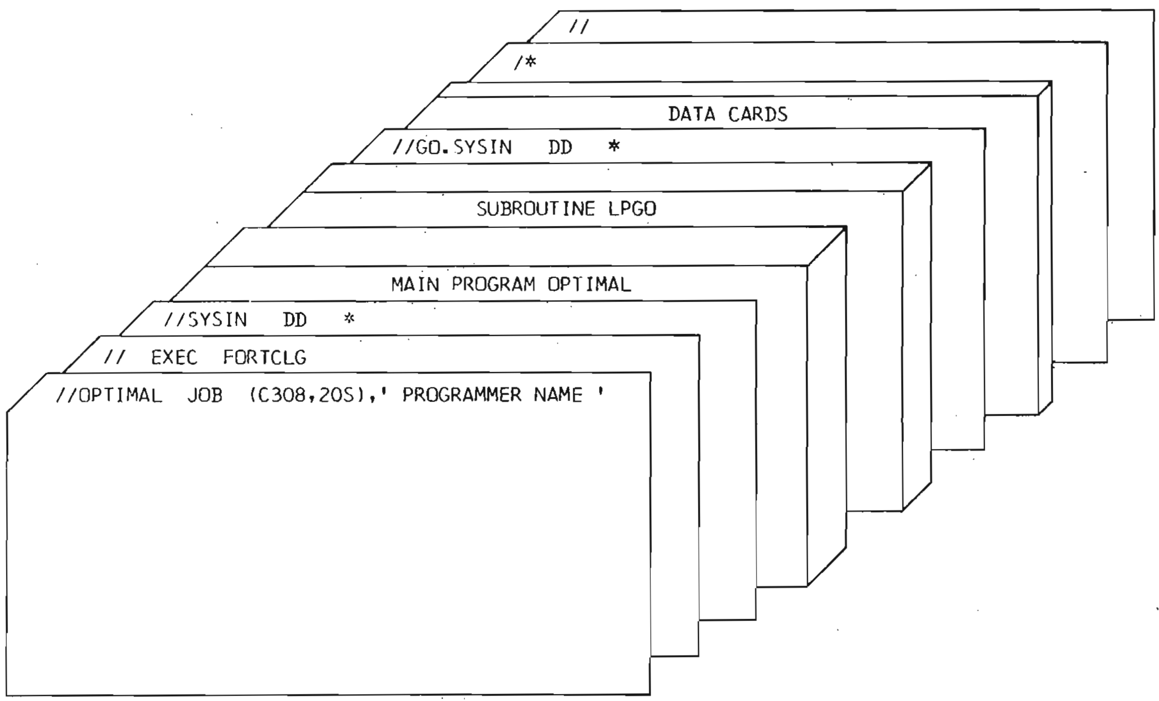
3. M constraint cards. Every card is identified by an equation name in the first 4 columns, so that the coefficients of one equation will not be mixed up with another.

    cols. 1-4, equation ID.
    cols. 11-80, divided into 7 fields with 10 columns each. II values are punched on this portion. Extend if necessary to additional cards which must be named for the reason mentioned above.

4. Next N cards. Each card is identified by a variable name in the first 4 columns. The rest of the card is the same as described in constraint cards.
5. The rest cards of the data deck are the coefficient matrices of linear equation; one card for one element. Each card is identified by an equation name and a variable name followed by the value of an element in matrix. Card for an element of value zero is not necessary.

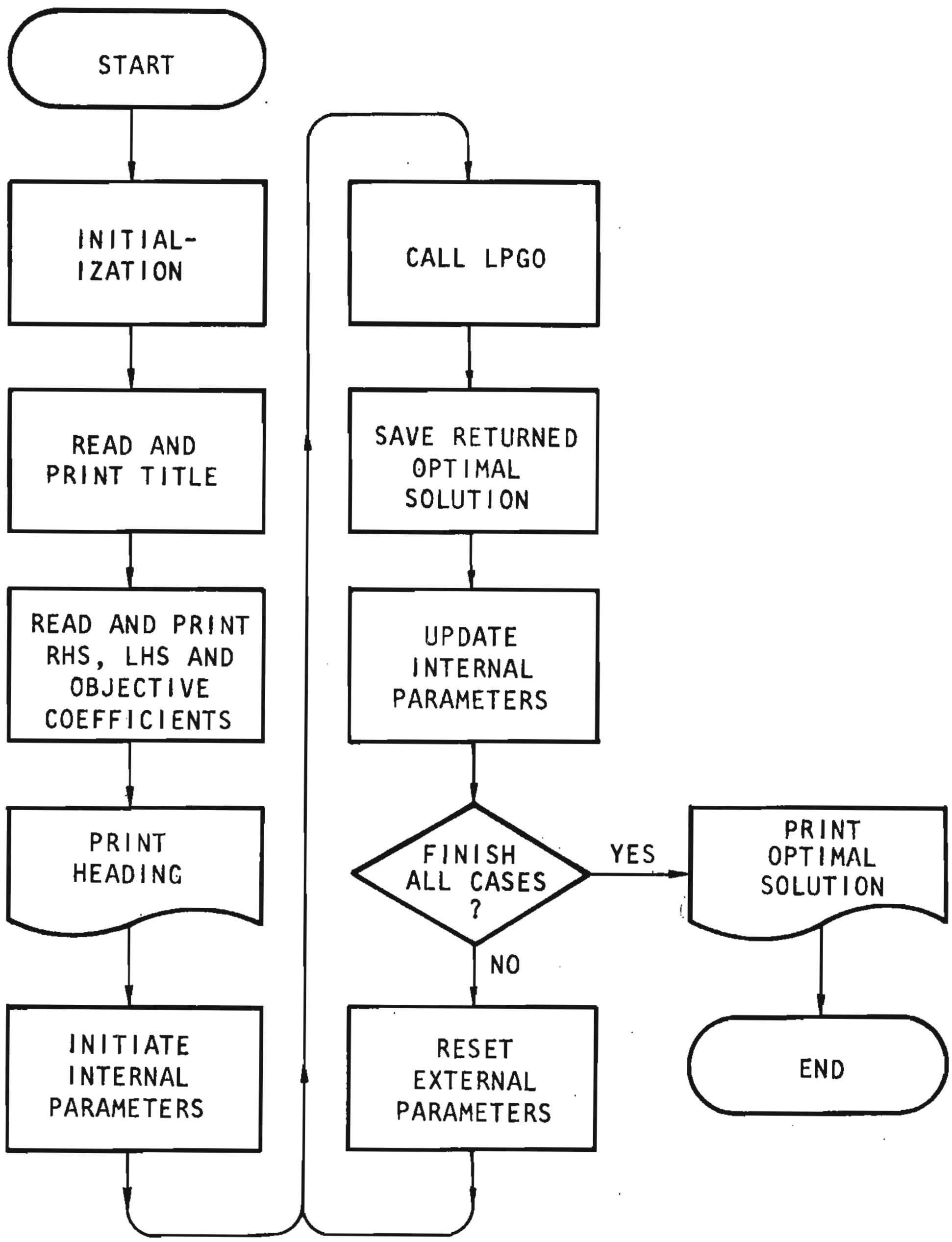
    cols. 1-4, equation name.
    cols. 9-12, variable name.
    cols. 21-30, value of single element in the matrix.

6. Last card. END1, the end of data card.

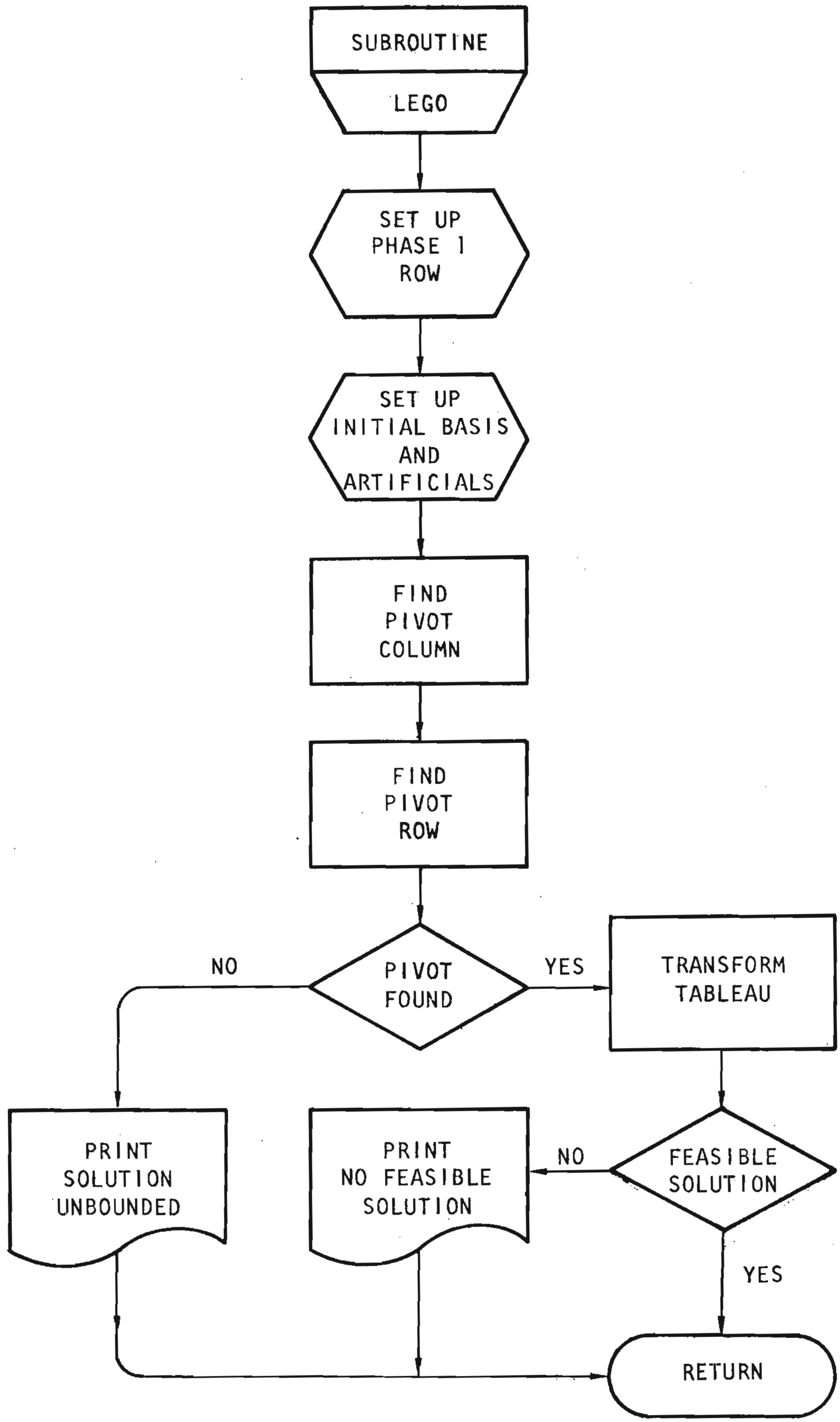



NOTE: THIS PROGRAM WAS TESTED AND RUN BY USING THE IBM 370/158 AT THE UNIVERSITY OF HAWAII. ANY CARDS STARTING WITH // AND /* ARE SYSTEM CONTROL CARDS AND MAY BE DIFFERENT FROM ONE INSTALLATION TO ANOTHER.

APPENDIX C. CARD ARRANGEMENT OF PROGRAM OPTIMAL




APPENDIX D.1. MAIN PROGRAM FLOW CHART




APPENDIX D.2. SUBROUTINE (LPGO) FLOW CHART

## Appendix E. Main Program and Definitions of Variables

```
IV  G LEVEL  21      MAIN              DATE - 75336           21/43/39

C       THIS IS MAIN PROGRAM.  THE CRITERIA FOR LINEAR OPTIMIZATION IS SET
C       UP AND THE LINEAR PROGRAM LPGO IS CALLED.  THE OPTIMAL SOLUTIONS ARE
C       SAVED AND PRINTED OUT AT THE END OF THIS PROGRAM.
C       THIS PROGRAM CAN HANDLE MORE THAN ONE (UP TO 20) SETS OF CONSTRAINTS
C       AND LHS COEFFICIENTS WITH A CONSTANT SET OF LINEAR EQUATIONS.
C
C       VARIABLES USED IN THIS PROGRAM ARE THE FOLLOWS:
C
C       A       WORKING MATRIX OF LHS COEF
C       AGL     LAND DISTRIBUTION OF INDIVIDUAL CROP
C       AGLT    TOTAL AGRICULTURAL LAND AVAILABLE
C       ARRAY   STORAGE POOL FOR ALL VARIABLES OF EQUATIONS (VAR)
C       B       WORKING MATRIX OF CONSTRAINTS
C       CON     MATRIX OF CONSTRAINTS
C       IEND1    END OF DATA SET
C       MAXA    MAXIMUM VALUE OF THE FIRST DIMENSION OF MATRIX A
C       NY      5 YEARS PERIOD
C       SOLU    OPTIMAL OBJECTIVE FROM LPGO
C       UAREA   URBAN AREA, ASSUMED TO BE CONSTANT
C       VAR     COEFFICIENTS OF LINEAR EQUATIONS
C
        DIMENSION AGL (10), VAR(22,70),CON(22,20),A(22,70),B(22),JCOL(20),
       1 IROW(20),ARRAY(20,20),IBASIS(20)
        INTEGER TITLE (20)
        DOUBLE PRECISION A,B,SOLU,RESULT,CON,VAR
C
C       CONSTANT INTERNAL PARAMETERS
C
        DATA MAXA/22/,NY/5/
        DATA IEND1/4HEND1/
C
C       INPUT
C
C       READ IN TITLE AND PRINT IT OUT
        READ(5,1001)(TITLE(L),L=1,20)
C
C       READ NUMBER OF EQUATIONS, NUMBER OF VARIABLES AND CASES
C
        ISTOP=0
        WRITE(6,1008)
        READ(5,1002)M,N,II,NS
        WRITE(6,1002)M,N,II,NS
        NM=N+M
        MPLUS1=M+1
        MPLUS2=M+2
        DO 5 I=1,MPLUS2
        DO 3 J=1,NS
      3 CON(I,J)=0.D0
        DO 5 J=1,NM
        VAR(I,J)=0.D0
```

```
    5 CONTINUE
C
C     READ EQUATION NAMES AND NONNEGATIVE RHS PARAMETERS
C
      DO 10 I=1,M
      READ(5,1004) IROW(I)'(CON(I,LL),LL=1,NS)
      WHITE(6,1011) IROW (I),(CON(I'LL)'LL=1,NS)
   10 CONTINUE
C
C     READ VARIABLE NAMES AND OBJECTIVE FUNCTION COEFS
C      THERE ARE NS SETS OF OBJECTIVE FUNCTION COEFS
C
      DO 20 J=1,N
      READ(5,1004) JCOL(J),(ARRAY(J,LL),LL=1,NS)
      WRITE(6,1011) JCOL(J),ARRAY(J,LL),LL=1,NS)
   20 CONTINUE
C
C     READ LHS COEFFICIENTS
C
   50 I2=0
      J2=0
      READ(5,1005) I,J,VALUE
      IF(I.EQ.IEND1) GO TO 67
      WRITE(6,1015) I,J,VALUE
      DO 60 I1=1,M
      IF(I.EQ.IROW(I1))GO TO 62
   60 CONTINUE
C
C     INCONSISTENT NAME FOUND IN DATA SET 1
C
      GO TO 700
   62 I2=I1
      DO  65 J1=1,N
      IF(J.EQ.JCOL(J1))GO TO 65
   65 CONTINUE
      GO TO 700
   66 J2=J1
      VAR(I2,J2)=VALUE
      GO TO 50
   67 WRITE(6,1009)
C     PRINT OUT HEADING FOR OUTPUT
C
      WRITE (6,1114)
      WRITE(6,1115) (JCOL(J)'J=1,II)
      WRITE(6,1116)
C
C     INITIALIZATION OF INTERNAL PARAMETERS
C
      K=0
      MM=1970
      UREA=600
      AGLT=21600
      DO 888 KK=1,NS
      DO 101 J=1,N
```

```
C  101  VAR(MPLUS1,J)=ARRAY(J,KK)
C
C       MOVE VAR INTO A AND CON INTO B
C
        DO 106 L=1,MPLUS2
        DO 106 J=1,NM
        A(L,J)=VAR(L,J)
   106  B(L)=CON(L,KK)
C
C
C       CALL LINEAR PROGRAM LPGO,RETURN WITH THE OPTIMAL SOLUTION
C       FOR EACH CROP, AND SAVE THEM FOR FUTURE USE
C
        CALL LPGO (MAXA,M,N,NM,MPLUS2,A,B,99,AGL,SOLU,IBASIS,IER)
C
C       IF IER IS 0, OPTIMAL SOLUTION FOUND
                  1, NO FEASIBLE SOLUTION
                 -1, SOLUTION UNBOUNDED
C
        IF (IER) 121,123,122
   121  WRITE(6,2003)
        STOP
   122  WRITE(6,2004)
        STOP
   123  WRITE(6,1105) MM,SOLU,AGLT,(AGL(I),I=1,II)
C
C       UPDATE INTERNAL PARAMETERS
C
   210  K=K+NY
        MM=1970+K
        AGLT=AGLT-UAREA
   888  CONTINUE
   999  STOP
C
C       IF INCONSISTENT NAME FOUND IN DATA SET 1 SET ISTOP=1 AND GO ON
C       READ THE REST OF DATA
C
   700  WRITE (6,1014)
        ISTOP=1
        GO TO 50
  1001  FORMAT(20A4)
  1002  FORMAT(4I4)
  1003  FORMAT(A4,12X,F12.6,I4,F10.2)
  1004  FORMAT(A4,6X,7(F10.2)/(10X,7(F10.2)))
  1005  FORMAT(2(A4,4X),F10.3)
  1006  FORMAT(1H1,20A4)
  1007  FORMAT(1H ,A4,12X,F12.6,I4,F10.3)
  1008  FORMAT(1H-,10HINPUT DATA)
  1009  FORMAT(1H ,'END OF DATA SET'///)
  1011  FORMAT(9X,A4,4X,5(F10.2)/(17X,5(F10.2)))
  1014  FORMAT(18H INCONSISTENT NAME)
  1015  FORMAT (1H ,A4,4X,A4,4X,F12.6)
  1105  FORMAT (1H ,I4,9X,F15.6,5X,F12.4,7X,10F12.4)
  1114  FORMAT (//////,1X,36HOPTIMAL SOLUTION FROM LINEAR PROGRAM)
```

```
 1115  FORMAT (1H-,4HYEAR,8X,17HMAXIMAL OBJECTIVE,' LAND AVAILABLE ',
      1 4X,10(8X,A4)//)
 1116  FORMAT (1H )
 1117  FORMAT (1H1)
 2003  FORMAT (1H-,19H SOLUTION UNBOUNDED)
 2004  FORMAT (1H-,21H NO FEASIBLE SOLUTION)
       END

*OPTIONS IN EFFECT*  ID,58CDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = MAIN     , LINECNT =       58
*STATISTICS*   SOURCE STATEMENTS = 95,PROGRAM SIZE = 33284
*STATISTICS*   NO DIAGNOSTICS GENERATED

       SUBROUTINE LPGO (MAXA,M,N,NM,M2,A,B,NC,C,SOLU,IBASIS,IER)
C
C      LPGO IS A MAXIMIZING LINEAR PROGRAMMING CODE,  IT USES THE TWO
C      PHASE, FULL TABLEAU FORM OF THE SIMPLEX METHOD, REQUIRES ALL RHS
C      PARAMETERS TO BE NONNEGATIVE, AND STARTS FROM A FULLY ARTIFICIAL
C      BASIS,  IT ASSUMES THAT ALL CONSTRAINTS HAVE BEEN CONVERTED TO
C      EQUATIONS STORED AS THE (M+1)ST AND (M+2)ND ROWS OF THE A ARRAY
C      WHICH ALSO STORES THE INVERSE OF THE BASIS IN ITS LAST M COLUMNS.
C
C      VARIABLES
C      A,     FULL TABLEAU OF THE SIMPLEX METHOD
C      B,     WORKING AREA OF CONSTRAINTS PLUS OPTIMAL SOLUTION IN THE
C             LAST ELEMENT
C      C,     LAND DISTRIBUTION
C      SOLU,  OPTIMAL OBJECTIVE
C      IER:   0, OPTIMAL SOLUTION FOUND
              1, NO FEASIBLE SOLUTION
             -1, SOLUTION UNBOUND
C
C      DIMENSION VARIABLES
C      M,     NUMBER OF CONSTRAINTS
C      MAXA,  FIRST DIMENSION OF A
C      NM,    SECOND DIMENSION OF A
C      N,     NUMBER OF VARIABLES (DECISION AND SLACK)
C      NC,    NUMBER OF CROPS BEING PROCESSED
C
       DOUBLE PRECISION A,B,DPS,RATMIN,RATIO,PIVOT,SOLU,DABS
       DIMENSION A(MAXA,NM),B(M2),C(NC),IBASIS(M)
       IER=0
       K=2
C
C      SETPU PHASE I ROW
C
       DO 120 J=1,N
       A(M+2,J)=0.D0
       DO 120 I=1,M
       A(M+2,J)=A(M+2,J)+A(I,J)
  120  CONTINUE
C
C      SET UP INITIAL BASIS AND ARTIFICALS
C
```

```
      DO 130 I=1,M
      NPLUSI=N+I
      A(I,NPLUSI)=1.D0
      IBASIS(I)=0
      B(M+2)=B(M+2)+B(I)
  130 CONTINUE
C
C     FIND PIVOT COLUMN
C
  399 DPS=0.D0
      MPLUSK=M+K
  400 DO 410 J=1,N
  405 IF(A(MPLUSK,J)-DPS)410,410,420
  420 DPS=A(MPLUSK,J)

C     THIS IS MAIN PROGRAM.  THE CRITERIA FOR LINEAR OPTIMIZATION IS SET
C     UP AND THE LINEAR PROGRAM LPGO IS CALLED.  THE OPTIMAL SOLUTIONS ARE
C     SAVED AND PRINTED OUT AT THE END OF THIS PROGRAM.
C     THIS PROGRAM CAN HANDLE MORE THAN ONE (UP TO 20) SETS OF CONSTRAINTS
C     AND LHS COEFFICIENTS WITH A CONSTANT SET OF LINEAR EQUATIONS.
C
C
C     VARIABLES USED IN THIS PROGRAM ARE THE FOLLOWS:
C
C     A      WORKING MATRIX OF LHS COEF
C     AGL    LAND DISTRIBUTION OF INDIVIDUAL CROP
C     AGLT   TOTAL AGRICULTURAL LAND AVAILABLE
C     ARRAY  STORAGE POOL FOR ALL VARIABLES OF EQUATIONS (VAR)
C     B      WORKING MATRIX OF CONSTRAINTS
C     CON    MATRIX OF CONSTRAINTS
C     IEND1   END OF DATA SET
C     MAXA   MAXIMUM VALUE OF THE FIRST DIMENSION OF MATRIX A
C     NY     5 YEARS PERIOD
C     COLU   OPTIMAL OBJECTIVE FROM LPGO
C     UAREA  URBAN AREA, ASSUMED TO BE CONSTANT
C     VAR    COEFFICIENTS OF LINEAR EQUATIONS
C
      DIMENSION AGL(10),VAR(22,70),CON(22,20),A(22,70),B(22),
     1 JCOL(20),IROW(20),ARRAY(20,20),IBASIS(20)
      INTEGER TITLE(20)
      DOUBLE PRECISION A,B,SOLU,RESULT,CON,VAR
C
C     CONSTANT INTERNAL PARAMETERS
C
      DATA MAXA/22/,NY/5/
      DATA IEND1/4HEND1/
C
C     INPUT
C
C     READ IN TITLE AND PRINT IT OUT
      READ(5,1001)(TITLE(L),L=1,20)
      WRITE(6,1006)(TITLE(L),L=1,20)
C
C     READ IN TITLE AND PRINT IT OUT
```

```
C
      ISTOP=0
      WRITE (6,1008)
      READ(5,1002)M,N,II,NS
      WRITE(6,1002)M,N,II,NS
      NM=N+M
      MPLUS1=M+1
      MPLUS2=M+2
      DO 5 I=1,MPLUS2
      DO 3 J=1,NS
    3 CON(I,J)=0.D0
      DO 5 J=1,NM
      VAR(I,J)=0.D0
    5 CONTINUE
C
C     READ EQUATION NAMES AND NONNEGATIVE RHS PARAMETERS
C
      JPIV=J
  410 CONTINUE
      IF (DPS-1.0D-06) 501,501,450
C
C     FIND PIVOT ROW
C
  450 RATMIN=1.0D+06
      IPIV=M+3
      DO 470 I=1,M
      IF(A(I,JPIV).L3.1.CD-06) GO TO 470
      RATIO = B(I)/A(I,JPIV)
      IF(RATIO.GE.RATMIN)GO TO 470
      RATMIN = RATIO
      IPIV=I
  470 CONTINUE
      IF(K.EQ.2) GO TO 476
      DO 475 I=1,M
      IF(IBASIS(I).NE.0)GO TO 475
      IPIV=I
  475 CONTINUE
  476 CONTINUE
      PIVOT=A(IPIV,JPIV)
      IBASIS(IPIV)=JPIV
C
C     IF PIVOT FOUND, TRANSFORM TABLEAU
C     IF NOT, EXIT, SOLUTION UNBOUNDED
C
      IF(IPIV.EQ.M+3)GO TO 496
      DO 500 I=1,MPLUSK
      IF(I.EQ.IPIV)GO TO 500
      DO 480 J=1,NM
      IF(J.EQ.JPIV)GO TO 480
      A(I,J)=A(I,J)-A(I,JPIV)*A(IPIV,J)/PIVOT
  480 CONTINUE
      B(I)=B(I)-A(I,JPIV)*B(IPIV)/PIVOT
      A(I,JPIV)=0.D0
  500 CONTINUE
```

```
      DO 495 J=1,NM
      A(IPIV,J)=A(IPIV,J)/PIVOT
  495 CONTINUE
      B(IPIV)=B(IPIV)/PIVOT
      GO TO 399
  496 IER=-1
      RETURN
  501 IF(K.EQ.1)GO TO 510
      IF(B(M+2)-1.0D-03) 504,504,505
C
C     NO FEASIBLE SOLUTION EXISTS
C
  505 IER=1
      RETURN
  504 K=1
      GO TO 399
C
C     OPTIMAL SOLUTION OUTPUT
C
  510 SOLU=-B(M+1)
      DO 580 J=1,NC
      DO 520 I=1,M
      II=I
      IF(IBASIS(I).EQ.J)GO TO 550
  520 CONTINUE
      C(J)=0.0
      GO TO 580
  550 C(J)=B(II)
  580 CONTINUE
 9000 RETURN
      END

*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = LPGO     , LINECNT =        58
*STATISTICS*   SOURCE STATEMENTS = 77, PROGRAM SIZE = 2564
*STATISTICS*  NO DIAGNOSTICS GENERATED

*STATISTICS*  NO DIAGNOSTICS THIS STEP

88-LEVEL LINKAGE EDITOR OPTIONS SPECIFIED   NONE
   DEFAULT OPTION(S) USED - SIZE=(06256,43008)
**USERPROG  DOES NOT EXIST BUT HAS BEEN ADDED TO DATA SET
```

INPUT DATA

5 9 4 11

| | | | | | |
|---|---|---|---|---|---|
| ALAN | 21600.00 | 21000.00 | 20400.00 | 19800.00 | 19200.00 |
| | 18600.00 | 18000.00 | 17400.00 | 16800.00 | 16200.00 |
| | 15600.00 | | | | |
| WATR | 86400.00 | 85000.00 | 81600.00 | 70200.00 | 76800.00 |
| | 74400.00 | 72000.00 | 69600.00 | 67200.00 | 64800.00 |
| | 62400.00 | | | | |
| ALBR | 1188.00 | 1155.00 | 1122.00 | 1089.00 | 1056.00 |
| | 1023.00 | 990.00 | 957.00 | 924.00 | 891.00 |
| | 858.00 | | | | |
| ALET | 190.00 | 200.00 | 200.00 | 190.00 | 190.00 |
| | 190.00 | 190.00 | 190.00 | 200.00 | 200.00 |
| | 210.00 | | | | |
| POTA | 930.00 | 780.00 | 670.00 | 610.00 | 580.00 |
| | 550.00 | 540.00 | 540.00 | 540.00 | 560.00 |
| | 580.00 | | | | |
| AL | 7210.00 | 8150.00 | 9680.00 | 11360.00 | 13060.00 |
| | 14600.00 | 15830.00 | 16940.00 | 18040.00 | 18940.00 |
| | 19530.00 | | | | |
| PO | 1000.00 | 1120.00 | 1330.00 | 1610.00 | 1970.00 |
| | 2300.00 | 2620.00 | 2920.00 | 3200.00 | 3460.00 |
| | 3670.00 | | | | |
| PI | 610.00 | 740.00 | 890.00 | 1070.00 | 1210.00 |
| | 1360.00 | 1470.00 | 1550.00 | 1530.00 | 1750.00 |
| | 1800.00 | | | | |
| C | 219.00 | 257.00 | 309.00 | 370.00 | 440.00 |
| | 500.00 | 560.00 | 610.00 | 650.00 | 690.00 |
| | 720.00 | | | | |
| X1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 0.0 | | | | |
| X2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 0.0 | | | | |
| X3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 0.0 | | | | |
| X4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 0.0 | | | | |
| X5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 0.0 | | | | |

| | | |
|---|---|---|
| ALAN | AL | 1.000000 |
| ALAN | PO | 1.000000 |
| ALAN | PI | 1.000000 |
| ALAN | C | 1.000000 |
| ALAN | X1 | 1.000000 |
| WATR | AL | 4.020000 |
| WATR | PO | 3.349999 |
| WATR | PI | 1.120000 |
| WATR | C | 5.000000 |
| WATR | X2 | 1.000000 |

```
ALBR     AL           0.500000
ALBR     PO           0.210000
ALBR     PI           0.119000
ALBR     C            0.041000
ALBR     X3           1.000000
ALET     AL           1.000000
ALET     X4           1.000000
POTA     PO           1.000000
POTA     X5           1.000000
END OF DATA SET
```

OPTIMAL SOLUTION FROM LINEAR PROGRAM

| YEAR | MAXIMAL OBJECTIVE | LAND AVAILABLE | AL | PO | PI | C |
|---|---|---|---|---|---|---|
| 1970 | 7116900.699874 | 21600.0000 | 190.0000 | 0.0 | 3558.5283 | 16330.1289 |
| 1975 | 8222930.091522 | 21000.0000 | 200.0000 | 0.0 | 3394.7053 | 15878.7852 |
| 1980 | 9615956.734867 | 20400.0000 | 200.0000 | 0.0 | 3273.4116 | 15425.9531 |
| 1985 | 11116178.548293 | 19800.0000 | 190.0000 | 0.0 | 3194.6467 | 14971.6367 |
| 1990 | 12488432.995369 | 19200.0000 | 190.0000 | 0.0 | 3073.3528 | 14518.8086 |
| 1995 | 13821789.739492 | 18600.0000 | 190.0000 | 0.0 | 2952.0588 | 14065.9766 |
| 2000 | 14797659.550012 | 18000.0000 | 190.0000 | 540.0000 | 1933.2070 | 13452.3984 |
| 2005 | 15533604.325212 | 17400.0000 | 190.0000 | 540.0000 | 1811.9133 | 12999.5703 |
| 2010 | 15178735.643319 | 16800.0000 | 200.0000 | 540.0000 | 1648.0903 | 12548.2266 |
| 2015 | 16681035.513898 | 16200.0000 | 200.0000 | 560.0000 | 1493.5537 | 12089.4414 |
| 2020 | 16938724.189168 | 15600.0000 | 210.0000 | 580.0000 | 1296.4880 | 11632.1445 |