12th International Conference on Hydroscience & Engineering
Hydro-Science & Engineering for Environmental Resilience
November 6-10, 2016, Tainan, Taiwan.

Optimal Cropping Patterns for Profit Maximization Using a Linear Programming Model: A Case Study in Njawara Village, The Gambia.

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ABSTRACT

Farmers in dry areas are often faced with the problem of how to select the optimal cropping pattern that significantly contributes to profit maximization. The problem arises, when they are confronted with the challenges of limited water to support plant growth. This present study attempts to formulate a Linear Programming model with the aim to maximize the farmers' net profit under a set of constraints (plant area and water). Data such as Agricultural data as well as Meteorological data were prepared and included in the data analysis. The study area covers 130 hectares, located in Njawara Village in Lower Baddibu District, North Bank Region (NBR) of the Gambia. The farm is cultivated by 5 main crops (millet, maize, sorghum, groundnut, and cassava) which are irrigated by groundwater extracted from five tube wells. The LP model is then formulated, with the objective to maximize the net profit of cultivation whereby the net profit implies the change between gross incomes (selling price of the product on the market) minus cost (farm inputs). The Lindo package was applied to solve the LP model. The results of the mathematical problem indicate that, compared with the present status of cultivation, 187 percent annual increase of the financial benefits can be achieved, when using the optimum cultivation pattern. From the results of the optimal cropping pattern, the water saved was calculated to determine the amount of water that can be saved per year, the results concluded that about 50% of water can be saved, which could be further economically utilized.

KEY WORDS: Linear Programming; Optimum cultivation pattern; Net profit; Water consumption

INTRODUCTION

Millions of people throughout the world are living in arid lands characterized as too dry for conventional rain fed agriculture. The dry land areas (40% of world land surface) are home to over 2 billion people, accounting for 35% of the world's population. More than 90% of dry land inhabitants are in the developing world and 70% in rural areas. In Africa, North of the Equator, Arid and Semi-arid zones are bordered by Senegal, the Gambia, Upper Volta and Chad in the South; and Morocco, Algeria, Libya, and Egypt in the North. These areas are characterized by low and inconsistent rainfall, periodic droughts and different vegetation and soil types.

Agricultural production in most dry regions experienced serious setbacks, resulting to low levels of farm revenue and food insecurity. In these areas agricultural yields are likely to be irregular, although grazing is satisfactory (Goodin & Northington, 2013). Inadequate water resources to support agricultural production is a major issue. Water scarcity is one of the key limitations to crop productivity and sustainability, thus water scarcity is one of the most major causes for agricultural problems in these dry regions. Yang et al., (2010) stated that, one of the main issues preventing further increase of food production will be water.

The Gambia lies in the Sahelian Agro-Climatic Zone characterized by low and irregular precipitation. The Average annual rainfall is 836 mm, with a spatial variation from over 1000 mm in the South to less than 800 mm in the North. From 1968 to 1990s, the country observed recurring episodes of drought and erratic rainfall (Sonko et al., 2016).

Statement of the Problem

The North Bank Region of The Gambia is one of the most vulnerable regions to drought due to low rainfall and patchy distribution of rainfall. The rainy season is short with less precipitation; it starts in June and ends in October. The nature of the rainfall pattern has a very negative impact on agricultural production in this area. It entirely affects the cropping pattern, poor harvests seriously threaten household food security and livelihoods (Yaffa, 2013) .

Agriculture is highly reliant on climate variability, (Salman et al. 2001) a phenomenon that has made the threat of climate change very urgent in Africa, (Parry, 2007) . Mendelsohn and Dinar (2003) , projected that by 2100, The Gambia and other West African countries are likely to have agricultural losses up to 40% of GDP due to climate change.

Agriculture in the Gambia is predominantly dependence on rainfall, with little or underdeveloped irrigation facilities to determine the cropping pattern especially in rural areas (Sonko et al., 2016). The rural farming activities are mainly smallholder and are characterized by poor farmers who appear to be strapped in a vicious cycle of poverty, (Kuyiah et al., 2016). Most rural farmers depend on experience and local knowledge to make decision on when to grow crops usually after the first rainfall. Their decisions does not reflect a good cropping pattern that may increase crop yield and farm income.

This research will apply the linear programming techniques under water and land constraints to help farmers make decision on optimal cropping pattern. Mathematical programming models are suggested for optimal allocation of scarce resources. L.P is well suitable for the analysis of water use in the agricultural activities. These models can deliver information on optimal cropping pattern in areas with scarce water. Outcomes of optimization can be used by agricultural planners and farmers to assess their cropping pattern, (Loucks et al., 2010).

Significance/ Justification of the Study

The agricultural sector is the most vital sector of the Gambian economy, contributing 32% of the gross domestic product, providing jobs and income for 80% of the population, and accounting for 70% of the country's foreign exchange earnings. It remains the major sector to raise income levels, for investments, to improve food security and decrease levels of poverty (Fatajo, 2010). However, low rainfall pattern is a major constrain to this important sector. Water is accessible to plants by precipitation and subsurface water, nevertheless, when these supplies are inadequate for crop use, farmers must respond rapidly to overcome this problem. Hence, finding ways to determine the optimal cropping pattern is essential for dry regions with shortage water resources such as the Gambia.

Objective

The Objective of this study is to formulate a linear programming model, to determine the amount of land for cultivating different crops, under water and plant area constraints, in order to maximize the net profit of cultivation, whereby the results are based only on this limitation and the assumption in the computer programing.

Research Questions

i. What is the Optimum Cropping Plan for the selected crops?
ii. How should farmers allocate their resources to optimize gross returns?
iii. Which crop (s) should be produced to attain the highest level of returns?

MATERIALS AND METHODS

Model Development

An optimal planning and management model involves identification of the decision variables, the constraints and the objective functions which are to be maximized or minimized. In this present study the objective function has three sets of constraints; Plant area, Groundwater availability and Minimal area.

The model relies on determination of the optimal cropping pattern under water deficit and land constraints. The optimal cropping pattern is transformed into a monetary value (net return per unit of crop area) in order to maximize the farm income.

Objective Function

The objective function for profit maximization is expressed as a difference between total income and total costs, multiply by area *Ai*. To establish the Objective Function (Z), the area A_i for each of the crops, must be multiplied by the net profit (X_i) per ha of each crop. The net profit is obtained from the difference between gross income and costs. The cost here implies the items for the farming activities and may affect the final profit (see Table 1). The decision variables consider in this study involves the area A_i of the different 5 crops, i.e. millet, maize, sorghum, groundnut, and cassava, for the 130 hectares farm. Algebraically the model is summarized below:

$$Max \quad Z = \sum_{i=1}^{n} A_i X_i \qquad (1)$$

where, A_i is the area under cultivation of each crop (decision variables) for the 130 ha farm. X_i is the net profit/ha of each agricultural product and n denotes the 5 crops that are considered i.e., maize, millet, sorghum, groundnut, and cassava (see Table 2).

Table 1 Cost ($) inputs for crop cultivation

No	Item	Unit	Cost
1	Donkey Horse Bull	item item item	98.40 636.59 405.14
2	Donkey cart	item	69.46
3	Seeds	kg	0.46
4	Cassava stems	kg	0.19
5	Hoe	item	2.34
6	Sine hoe	item	92.61
7	Seeder	item	115.76
8	Hand plough	item	0.56
9	Had hoe	item	1.74
10	Rakes	item	3.47
11	Axes	item	4.63
12	Mould plough	item	81.03
13	Cutlass	item	4.05
14	Hand knife	item	1.46
15	Fertilizer	kg	subsizied
16	Irrigation (wells)	item	subsizied

Table 2 Net Profit Xi ($) for each of the five crops use in the LP-model

Crop	Millet	Maize	Sorghum	Groundnut	Cassava
Xi($/ha)	623.43	439.41	388.66	839.72	3,137.48

Constraints

In setting up the LP problem, the assumption is that a series of linear constraints including the decision variables occur over the variety of alternatives being measured in the problem, (Chinneck, 2004) .

The problem is based on the most relevant factors that pose a constraint in agricultural production. Although in a real-world there is a large number of criteria that could affect agricultural production, this study is pondered on the following decision variables and constraints:

Constraint of Plant area. The first constraint has to do with the plant area AW_i covered by each of the 5 wells (j=1,…,5), the plant area is formulated together with the groundwater wells. The water withdrawer from each well is used only within its vicinity; hence the constraint is formulated for each of the 5 wells.

$$\sum_{i=1}^{5} A_{ji} \leq AW_j \tag{2}$$

where, A_{ji} is the decision variable i.e., the area to be planted for each crop *i* for LP-problem (well) *j*, AW_i denotes the corresponding covered area of well *j* (see Figure 3).

Table 3 Area AWj covered by each well

Well No.	1	2	3	4	5	Sum
Covered area (ha)	20	23	34	34	19	130

Constraint of Groundwater Availability. In this study, water availability to support plant production is considered a constraint. In the condition where the precipitation is a limiting factor, the groundwater is proposed for irrigation and the irrigation water requirement per crop has to be estimated. For the purpose of this study, reference evapotranspiration water is determined in relation to the FAO Blaney-Criddle method. The crop water requirement is calculated as a difference between crop evapotranspiration and effective rainfall (Brouwer & Heibloem, 1986).

The ET_o takes this general form:

$$ET_o = P.\ (0.46\ T+8) \tag{3}$$

where, ET_o = reference crop evapotranspiration (mm/d) as an average for 1 month
T mean = mean daily temperature (°*C*) over the month considered, and,
P= mean daily percentage of annual daytime hours

The crop evapotranspiration (ET_c) is calculated as a product of reference evapotranspiration (ET_o) and crop coefficient (*Kc*)

$$ET_o * K_c = ET\ crop \tag{4}$$

where, ET_c = crop evapotranspiration (mm/day) and Kc = crop coefficient. The latter have been selected from (Allen et al., 1998).

The Net Irrigation Requirement (mm/month) is then calculated by.

$$NIR = ET_c - P_e \tag{5}$$

where, P_e = the effective rainfall (mm/month). Based on these water crop considerations, the water availability constraint for all the 5 crops in each subarea supplied by well *j* for a particular month of the growing season (June to October) is given below:

$$\sum_{i=1}^{5} A_{ji} NIR_i \leq VW_j \times e \tag{6}$$

where, A_{ji} is as above, NIR_i is the water requirement of crop *i* for a particular month (mm/month), VW_j denotes volume of groundwater withdrawal from each well (m^3/month) see Table 4 and e is the named surface irrigation efficiency that is equal to 30%.
The calculated optimal water amount should be less than or equal to the amount of well-water withdrawn.

Table 4 Irrigation Water Requirement (mm/month) for each crop

Crop/month	June	July	August	September	October
Millet	95.00	17.23	8.32	55.00	0
Maize	95.00	41.72	8.32	55.00	111.97
Sorghum	95.00	17.23	8.32	55.60	0
Groundnut	106.30	81.71	48.00	36.90	0
Cassava	108.10	30.56	17.62	61.32	101

Table 5 Groundwater withdrawal from each well (m^3/month)

Well/month	June	July	August	September	October
1	9900	10000	10300	10200	8900
2	10100	10200	10300	9900	8900
3	10100	10100	10300	10100	9900
4	9900	10000	10200	10200	9900
5	9900	9900	10300	10200	10000

Constraint of Minimal area. This constraint implies the minimal area where specially required crops should be considered in the cultivation pattern to fulfill food requirement as well as livestock as indicated in Table 6.

Table 6 Minimal area

Well No.	Sorghum	Millet	Maize
Minimal cultivated area (ha)	20	23	34

RESULTS AND DISCUSSION

Statistical data outputs produced through a LINGO program, the linear programming problems for the individual wells are solved and the optimal cropping patterns for these areas have been calculated. The results in (Figure 1) illustrate the optimal cultivation areas for the 5 crops. It is observed from the figure that the optimal cultivation areas for cassava, maize, sorghum, millet, and groundnut are 85, 18, 15, 12 and 0 hectares, respectively. The results suggests that, groundnut should be omitted from the cultivation pattern.

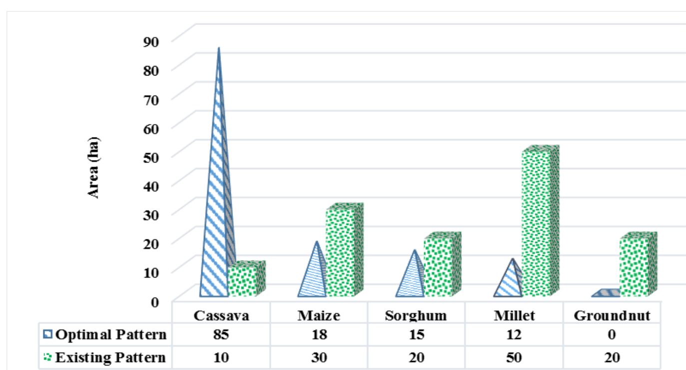

Fig. 1 Comparison of optimal cultivation pattern and current pattern

Net Profit

Table 7 lists the net profits for the optimal as well as the current cultivation pattern. The table shows that, with the optimal cultivation pattern, the net profit will increase by $ 187,610, which, when compared with the existing profit, amounts to an increase of 187%.

Table 7 Comparison of the net profits ($/ha) for the optimal (OP) and existing (EP) Pattern

Profit Crop/	Cassava	Maize	Sorghum	Millet	Groundnut	Sum
Net profit	3137.480	439.41	388.66	623.43	839.72	
Net profit OP	266685.80	7909.38	5829.90	7481.16	0	287906
Net Profit EP	31374.80	13182.30	7773.20	31171.50	16794.4	100296
Net Profit diff	235311.00	-5272.92	-1943.30	-23690.30	-16794.4	187610

Water saved

In this present study, water scarcity, raises the question, to whether the scarce groundwater resources in the study area can be further economized? It was therefore, necessary to examine the amount of water saved (see Figure 2).

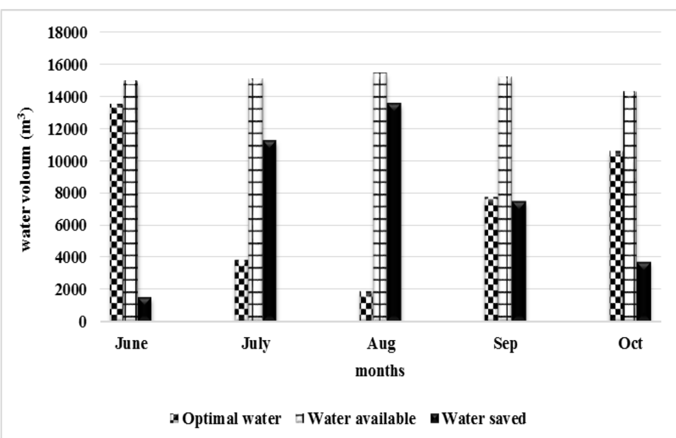

Fig. 2 Water saved (m^3) with the optimal pattern for each month

From Figure 2 it can be realized that, not much water can be saved in the month of June and October. In July and August, the water saved is huge compare to June, September, and October. This illustrates that, much water can be saved in July and August. This makes sense because the wet season starts in June and ends in October. Generally the first month of the raining season receives less precipitation compared to July and August. Furthermore, the water saved from the optimal cropping pattern shows that about 50% of water can be saved. The water could be used for other economic benefits such as small scale vegetables gardening, etc.

CONCLUSTIONS

Inadequate water resources to support agricultural production, is a major issue in dry areas. Farmers in these areas find it challenging to make decision on the cropping pattern. Most local farmers depend on experience and local knowledge to make decision on their cropping pattern, which neither give an optimal cropping pattern nor increase crop yield and farm income.

In this study the LP model was applied to give an optimal solution to the problem (i.e., determined the cropping pattern of the various crops included in the model). From the results of the optimal cropping pattern, cassava production must be increased in the study area in order to maximize the net income of the farmers, given the fact that the existing profit of this crop was the most attractive before and after the optimization. Also cassava is a drought tolerant crop, which means that this crop does not require too much water to grow.

The LP results further illustrate that, the optimal area of groundnut is Zero, suggesting that the crop is not economical and must be entirely eliminated from the optimal cropping pattern and its resources were reallocated to the other crops. Furthermore, with this optimal cultivation pattern, a 187% annual increase of the economic profit can be gained, when compared with the present cultivation pattern.

With regards to the water saved estimated by the optimal cropping pattern, about 37474 m^3 of water which is equivalent to 50% of the water can be conserved.

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