

Agriculture Crop Planning Under Land and Water Constraints: A Reproducible Linear-Programming Case Study of Brazil

Author Details:

Shardul Ghag¹, Ruhi Janani², Romit Shah³, Sanvi Jaiswal⁴, Sara Naikwadi⁵, Shambhavi Priya⁶

^{1,2,3,4,5,6} B.Sc. Finance/Anil Surendra Modi School of commerce/SVKM's NMIMS, Mumbai, India.

Corresponding Author Email: sghag890@email.com | ORCID: <https://orcid.org/xxxx-xxxx-xxxx-xxxx>



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Abstract—

This paper is based on an Operations Research approach and the literature on the problem of agricultural crop planning when land and water availability are limiting factors. The primary literature source is a linear-programming model created for Western Bahia, Brazil, to maximize agricultural net benefit, while accounting for crop choice, crop cycle timing, land, water, labour, machinery, capital, and hydroclimatic scenarios. To illustrate the procedure using readily available data, the official FAOSTAT data for Brazil for 2022 were downloaded for four crops: soybeans, maize, seed cotton, and dry beans. Crop yield observations and producer price observations were added, along with crop cycle and crop water coefficients reported by the primary study. Next, a planning LP was solved using the SciPy HiGHS linear-programming solver, leading to a transparent planning LP. The demonstration does not seek to calculate net profit because similar production

1. INTRODUCTION

Operations Research (OR) is a tool used to make decisions under conditions of limited resources competing for the limited resources available. The selection of crop areas on a farm or irrigation district is a natural OR problem because the land area, water

cost data for the same crops were not available in the official data that was downloaded. Cotton is chosen only due to the maximum planning capacity of 1000 ha and illustrative water capacities. When available water is reduced by 10% and 20%, the cultivated area under the two scenarios is 571.4 hectares and 507.9 hectares, respectively, as water availability is binding. Gross revenue drops to around 12.55 million and 11.30 million and 10.04 million Brazilian local currency units, respectively. The results illustrate the applicability of linear programming to the allocation of agricultural resources and also indicate the necessity of local costs, daily weather data, labour and machinery requirements and yield-response functions before the model can be utilized as a farm decision tool.

Keywords— Agriculture; Crop planning; Linear programming; Resource allocation; Water management.

availability, labour, machinery, capital, planting time and opportunities and markets are all limited. It's not only a question of what is biologically feasible. It is the combination of activities that results in the best outcome given the conditions of resources and risks experienced during the planning period.

The project brief must include a real-life example of an application of an OR technique, an explanation of the mathematical model, explanation of the method used to solve the problem and critical reflection on assumptions and limitations. This paper attempts to meet those requirements by considering agricultural crop planning in detail. The chosen primary article is about the competition for water in irrigated agriculture of Western Bahia, Brazil, where there is a lack of certainty in rainfall. The integrated use of hydroclimatic scenarios, linear programming modelling, and the solution of the resulting problems in Microsoft Excel Solver and LP Simplex method [1].

The present paper serves as having two aims. Firstly, it provides an explanation of the actual problem, formulation and results of the chosen article. Secondly, it offers a reproducible classroom demonstration, based on downloadable FAOSTAT data, which is independent. The demonstration is specifically designed to be less broad than the original farm model. It makes land and water becoming the binding resources and maximizes gross revenue. This decision is important both methodologically because it prevents the creation of production costs, and because it defines the limit between what has been observed, what is published and what is assumed when planning.

II. LITERATURE REVIEW

Western Bahia is a farming area of MATOPIBA of Brazil's frontier. In 2000-2020, the cultivated region was mainly occupied by soybean, maize, cotton and beans, accounting for about 94% of the cultivated area (Boninsenha et al.). They also note an important contrast between rainfed and irrigated production: rainfed production is subjected to risk of a shortened or delayed rainy season, while irrigated production is a relatively small part of cropland and has a disproportionately high agricultural value [1]. Making decisions on water allocation and planting time is an economically and socially significant process in these conditions.

The main paper introduces the concept of a decision variable as the area planted to a specific crop, production system, crop-cycle type and sowing period. It aims at achieving maximum net benefit which is the difference between revenue/ha and production cost/ha. Land, labour, machinery, capital and water are considered as constraints. Crop water demand is determined by the reference evapotranspiration, crop

coefficients and a crop-specific reduction factor. The model is tested for five farms and three municipalities under the normal rainfall scenario as well as under the scenario of rainfall delay (1, 2, 3 or 4 fortnights) and rainfall reduction (5-20%) [1].

Irrigated areas may have continuous or double cropping recommendations in a number of scenarios as irrigation can meet the crop water demand. The model sometimes suggests not planting in rainfed areas if the water deficit is substantial forecast. The authors report reductions in actual yields as high as 61% in the Sama farm compared with expected yield, in some instances, as an example of how a model can be useful in providing useful early warnings even when farmers make other decisions [1].

As per the project requirement, the literature base is thus directly connected to the project requirements. The primary article is not used as a guide to readily obtainable local coefficients for each country. Instead, it provides the conceptual structure, crop-water relationships, scenario logic, and an actual example of LP decision support in the real world. The independent contextual production and price observations are provided by FAOSTAT for the purpose of the reproducible demonstration [2].

III. METHODOLOGY

[A] Data and reproducibility

The official data portal of FAOSTAT offers food and agriculture statistics for countries and territories and covers the crop production and agricultural producer price domains [2]. The analysis excluded Brazil 2022, four items: Soya beans, Maize (corn), Seed cotton, unginne, and Beans dry. Harvested area, production and yield were provided in production records. The price records provided local currency unit prices per tonnes per annum. There were three stages to data preparation. Yield values reported by FAOSTAT in kilograms per hectare were divided by 1,000 to get tonnes per hectare. Second, gross revenue per hectare was determined by multiplying the yield with the producer price. Third, the crop-water coefficients were derived from the cycle duration, the average crop coefficient and the reduction factor provided in the main article, Table 3. This is an explicit reference evapotranspiration planning assumption of 5 millimeters per day for all crops used in the model since

a site-specific daily weather series was not downloaded for this classroom demonstration. This value is not observed on a national level in Brazil.

Table I: Brazil 2022 Data and Model Coefficients

Crop	Yield (t/ha)	Price (LC U/t)	Gross revenue (LC U/ha)	Cycle (days)	Kc	Kr	Water (m ³ /ha)
Beans	1.09	4308.4	4697	105	1.20	0.87	5481
Maize	5.21	1258.8	6557	135	1.00	0.88	5940
Cotton	3.84	5148.4	19770	210	0.90	0.80	7560
Soybean	2.96	2863.0	8459	135	0.70	0.80	3780

The observed FAOSTAT values and published crop-water structure have been compiled into a single table (Table I). In this formulation, the gross revenue coefficient is the highest for cotton. This does not imply that cotton is always the most profitable crop, it depends on which year it's measured, which producer-price measure, whether using gross or net revenue, the common ET₀ assumption, and the lack of agronomic diversification or market constraints.

[B] Mathematical formulation

The demonstration is a continuous linear program. Let i index the four crops and let x_i be the hectares allocated to crop i . The objective is to maximize gross revenue:

$$\text{Maximize } Z = \sum_i p_i x_i$$

where p_i is the gross revenue per hectare and x_i is the decision variable. The land constraint is:

$$\sum_i x_i \leq A$$

where A is the available planning area. The water constraint is:

$$\sum_i w_i x_i \leq W$$

where w_i is crop water demand per hectare and W is the available water capacity. Non-negativity is imposed by

$x_i \geq 0$. The base planning case uses $A = 1,000$ hectares and $W = 4,800,000$ cubic meters. These capacities are illustrative planning capacities introduced to test the allocation logic, they are not claimed to be measurements from one farm. For each crop, water demand is calculated as:

$$w_i = d_i \times ET_0 \times K_{c_i} \times K_{r_i} \times 10$$

ET_0 is the reference evapotranspiration in millimeters per day, K_{c_i} is the average crop coefficient, K_{r_i} is the reduction factor and the factor 10 makes the conversion from millimeters over one hectare to cubic meters. The fundamental equation of reference evapotranspiration, crop coefficient and crop water demand is the same in the primary paper, but more detailed temporal and site-specific data are required for the full application [1].

The demonstration is not as rich as the original published model. It involves maximizing net benefit, not gross revenue, and can encompass labour, machinery, capital, arable land, rain-fed land, and crop-cycling. The simplified model is selected to be replicated, as a reader can download the same FAOSTAT bulk file, look at the four selected crop records, perform the same coefficient calculations and solve the same set of two-constraint LP without proprietary farm records.

[C] Solution Methodology

This article selected and solved the LP applications using the LP Simplex method in Microsoft Excel Solver [1]. The following demo was solved using SciPy's linprog function and the HiGHS linear-programming backend in Python. Both methods are used to solve a continuous linear program. The computational steps were: to build the objective coefficients, to build the land and water constraint matrix, to then specify the right hand side capacities, to then impose the non-negativity of the decision variables and to finally convert the final solution back to maximum gross revenue.

Three different scenarios of water availability were checked. The normal water storage is 4.8 million cubic metres. Capacity (for 10% reduction): 4.32 million cubic metres. The capacity is 3.84 million cubic metres for the 20% reduction. The land capacity is identical for all scenarios, at 1000ha. This separates the effect of water availability and mimics the scenario logic in the

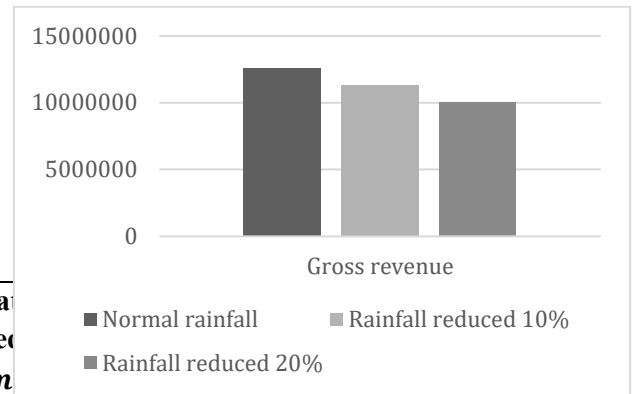
main article, but does not simulate dates of rainfall or crop yield response functions.

IV. RESULTS AND DISCUSSION

[A] Results

Table II: Optimal allocations and objective values

Scenario	Soyabean (ha)	Maize (ha)	Cotton (ha)	Beans (ha)	Total area (ha)	Water used (m ³ '0000)
Normal rainfall	0.0	0.0	634.9	0.0	634.9	48012552016
Rainfall reduced 10%	0.0	0.0	571.4	0.0	571.4	43211297335
Rainfall reduced 20%	0.0	0.0	507.9	0.0	507.9	38410042095



The outcome is quite meaningful in terms of OR interpretation. The model is not used to try to maximize the use of land, it is used to maximize the desired outcome within the bounds of the given resources. Since cotton has the highest gross-revenue coefficient, and all crops share the same land and water resources, the optimum corner solution is specialized. If the factors of crop rotation, biodiversity, food security, risk diversification, availability of labour, market absorption, etc. are significant, this solution would impose extra constraints or objectives in a real farm.

In each scenario, all the cultivated area is assigned to cotton by the LP. With normal water availability, 634.9 hectares of cotton crop can be sustained and then the water constraint of 4.8Mm³ becomes limiting. Water is the limiting factor, so the remaining land is not used. If water capacity decreases by 10%, then there is a decrease in cotton area by 571.4 hectares. If it has been reduced by 20%, the allocation would be 507.9 hectares. The gross revenue decreases by about 10.0% and 20.0% from the normal case, due to the same preference of the same crop and the reduction in water capacity proportionally.

Figure I: Optimal crop allocation under the three water-availability scenarios

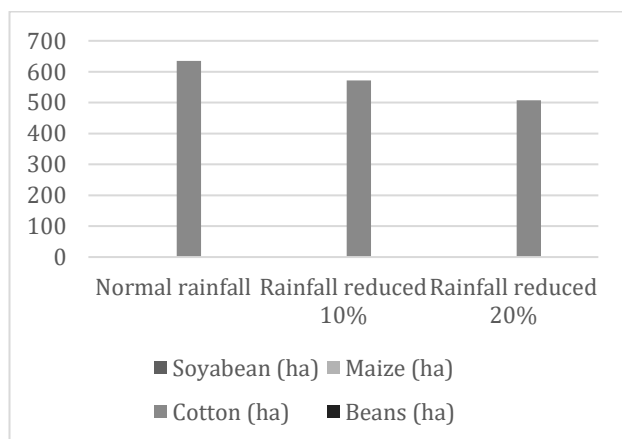


Figure II: Gross revenue under the three water-availability scenarios

[B] Critical analysis

The key benefit of using the LP approach is that it is clear. The decision variables are explicitly interpretable as hectares, each of the resource constraints represents an actual managerial constraint and the objective function expresses the economic criterion. LP also can be solved quickly and is easy to implement using available software like Excel Solver or Python. The method is appropriate for an agricultural planning study in which the mathematics and the managerial implications of the solution must be discussed.

Another one of the strengths is scenario analysis. The model structure may remain the same, but it may be changed to account for variation in water availability. Decision makers can then compare conditions of normal, delayed or reduced rainfall and determine when water is the limiting factor. The main article does this more realistically in terms of changing rainfall onset and rainfall-reduction scenarios, and allowing for distinction between irrigated and rainfed areas [1]. The present model does not simulate the entire hydroclimatic forecasting system, but rather the resource-scarcity logic.

The objective function is the most important constraint. This study relies on official data downloaded for this study that include production, yield, and producer prices, however, it does not include a consistent series of production costs for the four Brazil observations by crop. So, the model is useful for maximizing gross revenue, rather than net profit. This is a clear oversimplification, but the numerical recommendation should not be seen as a prediction of farm profitability. Crops might be changed in rank if the costs of sourcing seed, fertilizers, pesticides, irrigation, labour, machinery, land rent, and transport are included.

Another restriction is the water coefficient. Crop-cycle, Kc and Kr values are taken from the main paper and ET0 is assumed as 5 millimeters per day. Actual ET will vary with location and day and crop water demand will depend on weather, soil, irrigation efficiency, effective rainfall and crop stage. In the main article, it is pointed out that there are limitations due to linearity, biweekly decision periods, spatial variation, and limitation of the size of the Excel Solver. If applied in other parts of the country than Western Bahia, these issues are even more relevant.

The third restriction is the assumption of a continuous decision variable. No minimum field size, no crop rotation, no market limits, no contractual commitments and fractional hectares are allowed. It also does not include a single planning period nor does it model the time of cash flows. The assumptions are valid for an introduction to LP demonstration, but should be modified in an operational farm model. Discrete choices for fields or machines might be represented by mixed-integer programming, and multi-objective programming might be used to balance revenue, water use, risk and environmental outcomes.

[C] Extensions and Improvements

The first improvement could be to change the gross-revenue target to net benefit, with a locally verified cost budget for each crop. The second would be to use site-specific ET0 data, both daily and from a nearby station or a validated gridded product, instead of the common ET0 assumption. The third one would be to split the irrigation and rainfed decision variables, and add effective rainfall, irrigation efficiency and a water grant that can be legally granted. These changes would make the classroom demonstration more like the selected article.

More extensions would be: minimum production for staple crops, fortnightly labour and machinery limitations, price or yield risk penalty. Uncertainty in rainfall and prices could be represented by a stochastic or robust LP. A multi-objective model can be used to maximize income, while minimizing water usage or GHG emissions. The extensions make sense as research directions because they can be based on the clear LP base and resolve the limitations found in the literature and in this demonstration.

V. CONCLUSION

This study provides a practical illustration of the use of Linear Programming in analyzing agricultural crop planning as an actual resource allocation problem. The reviewed literature offers a compelling applied example of crop selection and sowing decision-making in Western Bahia, which is influenced by both water availability (scarcity) and precipitation variability (uncertainty). A reproducible demonstration of this model using 2022 FAOSTAT yield and producer price data for Brazil was developed with a Python based LP solver. Under the explicit assumption of planning, cotton is the main determinant of gross revenue, while water is the limiting resource. Water capacity reduction of 10% or 20% will result in a decrease in both feasible cultivated area and gross revenue in about the same percentage.

The results should be viewed as an example of a process for creating educational models of decision-making, rather than a specific recommendation to one farmer. The usefulness of the model lies in its documentation of the data used, the unit systems employed, the formulas applied, the assumptions made, the solver used, and the resulting output. What makes this a good learning tool is that all of the components of the model have been documented. A model that can be used to make decisions will require local cost information, site-specific weather information, irrigation efficiency information, labour information, machinery information, market information, rotation information, and risk information. The differentiation between the two types of models enhances the analysis by showing how useful OR can be, as well as how critical it is to validate the inputs into the model prior to using the optimization results in practice.



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