The effect of planning horizon length and green manure on net income in Crop Rotation Problem

Akouyo Yvette Gbedevi[1], Kossi Atchonouglo[1], Sid Ahmed Lamrous[2] and Marie-Ange Manier[2]

[1]Université de Lomé, Laboratoire d'Analyse et de Modélisation Mathématiques et Applications (LAMMA), Lomé, Togo
[2]Université de Technologie Belfort-Montbéliard , FEMTO-ST , Belfort, France

Abstract

The world population is increasing rapidly, and recent awareness of the limits of natural resources and the pollution of soil, air and water, is pushing towards a new form of agriculture, sustainable agriculture. Sustainable agriculture can be defined as an agriculture that combines environmental, social and economic objectives for the well-being of farmers and the soil. Crop rotation took hold during this decade by emphasizing the management of soil resources, while improving economic, environmental and social factors. The goal of the crop rotation planning problem discussed in this paper is to maximize the total net return, with a particular emphasis on incorporating a plant that contributes green manure to the soil alongside nutrient amendments by choosing the best horizon for plannification. The rotations generated are of fixed duration for all the plots and the objective is to maximize the income of the farmers. The results showed that the determined algorithm was feasible.

Keywords

Sustainable Agriculture, Crop Rotation Problem, Mixed-Integer Linear Programming, Optimization

1. Introduction

Agriculture is the main occupation in many countries around the world and with a growing population, which the UN projects will increase from 7.5 billion to 9.7 billion in 2050 [1]. This means that farmers will have to do more with less. According to the same survey, food production will have to increase by 60% to feed two billion more people. However, traditional methods are not enough to handle this huge demand. This drives farmers and agricultural businesses to find new ways to increase production while conserving soil resources. The challenge is to increase global food production by 50% by 2050 [2] to feed two billion more people by practicing sustainable agriculture.

Crop rotation is a fundamental feature of all organic farming systems. Crop rotation means changing the type of crop grown in a particular piece of land from year to year. There are cyclical rotations that repeat the same sequence indefinitely, and noncyclical rotations that allow for changes in crop sequence, adapting to management decisions and evolving as market opportunities arise [3]. Greater soil fertility, fewer pests and crop diseases, and higher yields are just a few of the positive outcomes of rotation. Compared to continuous monoculture practices, according to [4] , rotation increased crop yields by 20 % on average and the benefits are highly context-dependent.

The financial stability of the agricultural sector could be improved by including a variety of cropping strategies. The profits of the farm would not be based solely on a single primary cash crop; rather, they would be based on a diverse collection of commercial crops that were evenly distributed over a number of periods. This could eventually lead to an improvement in cash flow by introducing regular incomes into the agribusiness [5].

In order to assist the farmer in choosing the appropriate crops for the rotation cycle, we proposed a Mixed-Integer Linear Programming (MILP) model to solve the crop rotation problem by exploring the benefit of including green manure. We studied the importance of including fertilizer plants in crop

Proceedings of the DAAfrica'2024 workshop

*Akouyo Yvette Gbedevi.
†These authors contributed equally.
rosettegbedevi@gmail.com (A. Y. Gbedevi); katchonouglo@univ-lome.tg (K. Atchonouglo); sid.lamrous@utbm.fr (S. A. Lamrous); marie-ange.manier@utbm.fr (M. Manier)
0000-0002-5996-7027 (A. Y. Gbedevi)

rotation schedule by using exact methods such as linear programming to determine the best solution of the proposed agricultural model and to test it in a real context. The experiment was conducted for a real planting area of average size with 9 plots, considering 8 crops from different botanical families and a two-year, three year and four year planting rotation.

2. Literature Review

Maximizing the overall net return is the aim of the crop rotation planning problem that they address in [6]. The branch and bound approach is used to optimize the crop rotation plans in an integer linear programming model. In addition to the agronomic, water supply, and seasonal demand constraints, the suggested model includes a new temporal preference constraint.

In order to optimize the efficiency of organic farming in the Philippines' second and third largest agricultural land areas, the authors suggested using a Mixed Integer Programming model as a decision-making tool. This tool considers a number of organic farming-related factors. With the matching profit organic farms may make from planting them, the best-selling and most popular produce in the area is used [7].

Using a mixed integer linear programming model, their work [8] examines the crop rotation problem with water supply/demand and net return uncertainties that fluctuate within the permitted rotation cycle. It renders the developed model numerically feasible, mainly when applied to intricate agricultural issues. Determining the best cropping plans, providing a fair income for the farmer, and strategically accounting for water uncertainties are the primary goals of this endeavor.

In order to optimize crop rotation in conventional organic farms with plot adjacency constraints and nutrient amendments, this work [9] makes use of real-world data and the CBC solver. The goal of the created rotations is to maximize farmers' income, and they have set durations for each plot. The suggested agricultural model's solution is found using a linear programming technique.

In this study [10], the authors examine the Crop Rotation Problem and its applicability to the combination of farm management and Precision Agriculture. They increased the problem's appeal for sustainability by presenting a novel mathematical method for the CRP based on crop requirements and nutrient balance. To optimize the CRP, a real-encoded genetic algorithm was created. The findings show that mid- and long-term crop scheduling performed well.

A binary nonlinear bi-objective optimization model is presented in [11] to address the issue of agricultural cultivation planning that is sustainable by using a meta-heuristic technique based on a genetic algorithm and constructive heuristics. A planting schedule for crops to be grown in designated plots to limit the likelihood of pests proliferating and increase the process's profitability.

An integrated strategic-tactical planning model for the supply chain issue involving sugar beets is presented by the authors this study. In order to minimize the overall operational costs, including transportation and inventory of processed and unprocessed beets, a binary integer programming model is developed . To enable crop rotation planning across many cropping seasons, a special temporal dimension was introduced to the planning horizon [12]

3. Methodology

3.1. Study Area

According to FAO's annual report in 2006, nearly 69% of the 56,600 km2 of the Togolese territory is agricultural land, and 38% of this land is exploited. Rain-fed agriculture is practiced in Togo, and nearly 75% of the country's working population works as small farmers using traditional farming techniques. The two principal crops are maize in the south and focus of the nation and sorghum/millet in the north. 70% of the country's population, or 5.75 million people in 2010, is supported by agriculture, which also makes up nearly 40% of the country's GDP. From the south to the north, Togo is divided into five regions: the Maritime, Plateaux, Central, Kara, and Savanes. From one region to the next, pedoclimatic conditions and the availability of agricultural production factors, particularly land, vary significantly [13]. Togo's climate is tropical, and it varies a lot from south to north. The climate is sub-Sahelian (hot and dry) in the north, sub-Sahelian (rainy) in the center, and Guinea-Sudanian (hot and humid) in the south. The regions' intra-annual rainfall distribution is also unique. There are two rainy seasons in the Maritime and Plateaux regions each year *March/April to July and September to mid-November* and two dry seasons *August and mid-November to March/April* with 900 and 1500 mm of precipitation per year. There is a dry season from *November to April* in the Central, Kara, and Savanes regions, with annual rainfall ranging from 1200 to 1500 mm. As a result, there are two agricultural seasons in the southern parts of Togo, while there is only one in the northern parts. Despite the significance of agriculture to the Togolese economy, it has remained traditional and lacked access to organic and mineral fertilizers. Agricultural production includes:

- **Cereals**: Maize, Millet, and Sorghum
- **Tubers**: Yams and Cassava
- **Legumes**: Beans, Groundnuts, and Soya

Our research focuses primarily on the subtropical climate of the region, taking into account the potential crops.

3.2. Problem Description

Several factors, including market demands, soil characteristics, and crop nutrient requirements from a climatic perspective, are taken into consideration when choosing a cropping sequence. Plots are used to divide an agricultural area. Different kinds of crops can be grown on each plot [14]. Planning crops on agricultural land while taking into account the primary factors that affect crop yields (economic, environmental, and ecological) presents a challenge when developing a crop rotation system [9]. Utilizing the principles of crop rotation to make farmers as much money as possible while taking into consideration restrictions based on demand, crop characteristics, production times, and plot conditions is the primary objective of this work. The proposed model takes into account the following constraints:

1. **Sowing Period :** It is essential to observe each crop's sowing and production times.
2. **Cultural continuity among families:** Different botanical families contain the cultures. It is not recommended to grow cultures from the same botanical family in succession on the same plot [5]. This issue is primarily brought about by the fact that crops in the same family have similar deficiencies (the risk of acquiring the same diseases or weeds) and nutrient requirements. The cropping system's ability to last is jeopardized as a result of this.
3. **Crops belonging to the same family's neighbors:** On two adjacent plots, two crops belonging to the same botanical family cannot be sown simultaneously [5]. Characteristics are shared by cultures of the same family. Therefore, staking them simultaneously on two plots that are adjacent to one another is the same as staking the same crop on these two plots. This makes more resources available to pests, which in turn increases their population and the damage they can cause.
4. **Needs for nutrients:** The quantity of soil nitrogen, phosphorus, and potassium required to start a crop at any given time is referred to as its nutrient requirements. We define the nutrient of a crop as the quantity of nitrogen, phosphorus, and potassium that this crop requires, and the nutrient of a plot as the amount of nitrogen, phosphorus, and potassium applied to this plot over a specific time period.
5. **Fertilization with plants:** In the same rotation cycle, combining legumes with other crops has a positive effect on the soil and, as a result, increases yield.
6. **Fallow Period:** To allow the soil to regain its moisture and fertility, each cycle ought to include one or more periods of fallowness.
7. **Market demand:** The distribution of cash crops is significantly restricted as a result of this. Each culture has a preexisting market; the demand needs to be met.

Table 1
List of Index.

Index	Description
i	relatifs aux cultures
j	relatifs aux parcelles
t	période de l'horizon de planification
p	lié à la famille botanique des plantes
α	lié à l'intervalle de fertilisation, $\alpha \in \Omega, \Omega = \{\alpha \in \mathbb{N}^* \mid \alpha \cdot \theta \leq T, \theta \in \mathbb{N}^*\}$

The crop rotation problem is a complicated combinatorial optimization problem that changes depending on the model's scope, considering the aforementioned constraints. Along the rotation cycle, it is desirable to determine the best crop combinations to plant in each plot at each time. The problem is solved using the constructed mathematical model, and the following decisions are made:

- Determine the crop-specific area needed to satisfy demand.
- During the rotation cycle, determine the crop sequence in each plot.
- Obtain the various agricultural operations' calendar.

The crop rotation problem is a complicated combinatorial optimization problem that changes depending on the model's scope, considering the aforementioned constraints. Along the rotation cycle, it is desirable to determine the best crop combinations to plant in each plot at each time. The problem is solved using the constructed mathematical model, and the following decisions are made:

- Determine the crop-specific area needed to satisfy demand.
- During the rotation cycle, determine the crop sequence in each plot.
- Obtain the various agricultural operations' calendar.

4. Mathematical Modeling of the problem

The planting area is thought to be divided into plots by us. If two parcels share a boundary that is not reduced to a discrete set of points, they are neighbors. We will consider the opposite plots to be adjacent, for instance, if the planting area is divided into four plots.

A crop rotation schedule with a clearly defined planning horizon (T) is established by a producer with the intention of maximizing profits following an agricultural season. It has a number of crops (N) that are part of various botanical families (p), where F(p) is the number of crops in the family (p) and surfaces that are divided into plots (K) and naturally contain certain amounts of nutrients (Nitrogen, Phosphorus, and Potassium). Profitability (l), production cost (CP), production time (Z), average production (Q) per hectare, market demand (D), and nutrient requirements are all associated with each crop. Additionally, the farmer is restricted by the following restrictions: sowing time, continuity and neighbor for crops belonging to the same family, green fertilization, and fallow time.

The tables define all indices 1, parameters/data, and variables 2 for the proposed model.

The index of fertilization (α) is determined by the model parameters fertilization interval (θ) and planning horizon (T). For instance, if the planning horizon is 24 periods and the fertilization interval is 12 periods (θ = 12), then the set Ω is 1, 2 because α = 1 and α = 2 satisfy the definition of $\alpha \cdot \theta \leq T$.

The entire model is displayed below. The benefits of crop planning (calendar), the costs of fertilization, and other production costs (land preparation, transportation, labor) are evaluated by the objective function in Equation (1). Fertilization costs are also included in, with the goal of reducing reliance on external chemical fertilizers.

Subject to (1)-(15).

Table 2
List of Parameters.

Parameters	Description
N	number of crops to plant(N>=2)
K	number of plots (lot) available
T	the horizon (Duration) of planification
V	Set of crops for green fertilization
n =N+1	represents a fictitious crop imposing a fallow
F_P	Set of family cultures *p*, *p*= 1, ..., N_f
N_f	Number of crop families
$Surf_j$	Area of the plot *j* in *ha*
l_i	Crop profitability *i* per *ha* (FCFA XOF)
z_i	Crop production cycle *i* including the sowing period and the harvest period
Q_i	Crop Production Average *i* per ha
I_i	Crop sowing interval including earliest and latest period *i* {$I_i 1, \ldots, I_i n$
D_i	Crop demand *i* (unit/period)
S_j	Adjacent plots to the plot *j*
$F_N \alpha ij$, $F_P \alpha ij$, $F_K \alpha ij$	Dose of Nitrogen, Phosphorus and Potassium to bring to the plot *j* on interval α according to crop *i* .
$B_N j$, $B_P j$, $B_K j$	Initial composition of the soil in Nitrogen, Phosphorus and Potassium of the plot *j* per ha.
$R_N i$, $R_P i$, $R_K i$	Crop requirements *i* in Nitrogen,Phosphorus and Potassium
C_N, C_P, C_K	Cost of fertilisation in (FCFA par ha)
F_{mini} , F_{maxi}	Limit of fertilization for crop *i*
θ	Fertilization equilibrium interval (Compensation)
OC_i	Other production costs incurred on plot *j* at period *t* due to crop *i*. (Preparation of the land,purchase of seeds for sowing, transport, labor)

$$\sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{K} Surf_j * l_i * x_{itj} - \sum_{\alpha\in\Omega}\sum_{j=1}^{K}(F_{N\alpha ij} * C_N + F_{P\alpha ij} * C_P + F_{K\alpha ij} * C_K) - \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{j=1}^{K} OC_i * x_{itj}. \quad (1)$$

$$\sum_{i=1}^{N}\sum_{r=0}^{zi-1} x_{i(t-r)j} \leq 1. \quad (2)$$

$$\textit{With } t = 1, \ldots, T; j = 1, \ldots, K.$$

It is not allowed to plant two crops in the same plot [15, 16, 10]. Indeed, a crop occupies the entire plot throughout its growth and harvest. The constraint defined in equation (2) forbids scheduling more than one culture during the same period. There is a spatial constraint.

$$\sum_{i\in F_{(p)}}\sum_{r=0}^{z_i-1}\sum_{v\in S_j} x_{i(t-r)v} \leq K\left(1 - \sum_{i\in F_{(p)}}\sum_{r=0}^{z_i-1} x_{i(t-r)j}\right). \quad (3)$$

$$\textit{With } p = 1, \ldots, N_f; t = 1, \ldots, T; j = 1, \ldots, K.$$

It is not recommended to plant two crops from the same botanical family on adjacent plots at the same time [15, 9, 16, 10]. The fact that the cultures of the same family share characteristics is the source of this issue. Therefore, planting them simultaneously on two plots that are adjacent to one another amounts to planting the same crop on both plots, which does not maximize crop distribution on the various plots. If a crop *i* of the same botanical family *p* has already been sown on plot *k*, constraint (3) states that the number of crops on all plots S_j adjacent to plot *j* during their production periods Z_i must be equal to zero; otherwise, the number of crops is at most equal to the number of independent plots.

$$\sum_{i\in F_{(p)}}\sum_{r=0}^{z_i} x_{i(t-r)j} \leq 1. \quad (4)$$

$$\textit{With } p = 1, \ldots, N_f; t = 1, \ldots, T; j = 1, \ldots, K.$$

On the same plot, cultures belonging to the same botanical family cannot be grown immediately [15, 16]. This issue is primarily brought about by the fact that crops in the same family have similar deficiencies (the risk of acquiring the same diseases or weeds) and nutrient requirements. The cropping system's agronomic viability is jeopardized as a result of this. Constraint in equation (4) sets a maximum of one crop as the sum of all crops i in the botanical family p over their production period Z_i.

$$\sum_{i \in V} \sum_{t=1}^{T} x_{itj} \geq 1 \tag{5}$$

$$\textit{With} j = 1, \ldots, K.$$

Additionally, green manure improves the structure and fertility of the soil while also enhancing its organic matter enrichment [16]. Green manure adds nitrogen to the rotation by planting legumes [17]. Constraint (5) guarantees that every plot gets at least one implementation of green manure (legumes).

$$\sum_{t=1}^{T} x_{ntj} \geq 1. \tag{6}$$

$$\textit{With } n = N + 1, \quad j = 1, \ldots, K.$$

The period of frost or fallow enables the plot to restock its production capacity, water reserves, and other resources. as well as to restrict excessive agricultural production. Constraint defined in equation (6) ensures that each plot has at least one freezing period. During the frost period, there are no restrictions on neighborhood and consecutive planting.

$$\sum_{j=1}^{K} \sum_{t \notin I_i} x_{itj} = 0. \tag{7}$$

$$\textit{With } i = 1, \ldots, N.$$

Following the recommended planting date is critical for allowing the crop to express its yield potential and lowering crop protection costs. By preventing allocation outside of this window, the constraint outlined in equation (7) ensures that crop scheduling takes place only during the appropriate sowing period.

When nutrients are present in sufficient quantities and in mineral forms that can be absorbed by plants, a soil is more fertile [9]. They deplete the soil of the essential nutrients they require as they grow.

$$F_{N\alpha j} - \sum_{i=0}^{N} \sum_{t=1+(\alpha-1)*\Theta}^{\alpha*\Theta} x_{itj} * Surf_j * (R_{Ni} - B_{Nj}) \geq 0. \tag{8}$$

$$\textit{With } t = 1, \ldots, T; \alpha \in \Omega.$$

$$F_{P\alpha j} - \sum_{i=0}^{N} \sum_{t=1+(\alpha-1)*\Theta}^{\alpha*\Theta} x_{itj} * Surf_j * (R_{Pi} - B_{Pj}) \geq 0. \tag{9}$$

$$\textit{With } t = 1, \ldots, T; \alpha \in \Omega.$$

$$F_{K\alpha ij} - \sum_{i=0}^{N} \sum_{t=1+(\alpha-1)*\Theta}^{\alpha*\Theta} x_{itj} * Surf_j * (R_{Ki} - B_{Kj}) \geq 0. \tag{10}$$

$$\textit{With } t = 1, \ldots, T; \alpha \in \Omega.$$

The quantity of nitrogen, phosphorus, and potassium that the soil requires to initiate a crop at any given time is referred to as the minimum nutrient requirement. A plot's nutrient amendment is defined here as the amount of nitrogen, phosphorus, and potassium applied to it over a specific time period. Let

α be the size of the interval that is appropriate for sowing crop *i*, the interval that is used to apply the amendments $F_{N\alpha j}$,$F_{P\alpha j}$ and $F_{K\alpha j}$, B_{Nj},B_{Pj} and B_{Kj}, which represent the initial composition of the Nitrogen, Phosphorus, and Potassium soil of plot *j* per ha [10, 9] , R_{Ni} ,R_{Pi} and R_{Ki}, which represent the minimum amount of nutrients that crop *i* requires.

Equations (8), (9),(10) are used to calculate fertilization balances based on the surface nutrient budget.

$$\sum_{j=1}^{K}\sum_{t=1}^{T} Surf_j * Q_i * x_{itj} \geq D_i. \tag{11}$$

$$\textit{With } i = 1, \ldots, N.$$

Demand from the market is another significant constraint. The farm's crop yields are constrained by this constraint to meet the anticipated demand for the crop *i*. To avoid issues like prolonged product storage or conservation, which can result in additional costs and increase the risk of income variability, we believe that the farmer should not exceed the estimated demand. The constraint outlined in the equation (11) is used to evaluate the crop's production requirements.

Each of the Boolean decision variables x_{itj} represents the schedule (planning) of crop *i* during period *j* on plot *t*. When and where crops are planted are tracked by them. The variables of fertilization $F_{N\alpha j}$,$F_{P\alpha j}$ and $F_{K\alpha j}$ are actual variables.

$$x_{itj} \in \{0, 1\}. \tag{12}$$

$$\textit{With } i = 1, \ldots, N; \quad t = 1, \ldots, T; \quad j = 1, \ldots, K.$$

$$F_{N\alpha j} = \left\{F_{N\alpha j} \in \mathbb{R}^{+} \mid F_{Nmax} \geq F_{N\alpha j} \geq F_{Nmin}\right\}. \tag{13}$$

$$\textit{With } j = 1, \ldots, K; \alpha \in \Omega.$$

$$F_{P\alpha j} = \left\{F_{P\alpha j} \in \mathbb{R}^{+} \mid F_{Nmax} \geq F_{P\alpha j} \geq F_{Nmin}\right\}. \tag{14}$$

$$\textit{With } j = 1, \ldots, K; \alpha \in \Omega.$$

$$F_{K\alpha j} = \left\{F_{K\alpha j} \in \mathbb{R}^{+} \mid F_{Nmax} \geq F_{K\alpha j} \geq F_{Nmin}\right\}. \tag{15}$$

$$\textit{With } j = 1, \ldots, K; \alpha \in \Omega.$$

5. Model discussion and analysis

5.1. Tools

Python-MIP, a collection of Python tools for modeling and solving Mixed-Integer Linear Programs (MIPs), was used for the model's implementation and evaluation and CBC Solver as Solver since it does not require a license unlike Gurobi. The solver uses the branch and bound algorithm to find the optimal solution for the crop rotation problem. The study will focus on eight crops from five botanical families. Crop data, as well as production parameters like planting, harvesting dates and nutrient requirements, are listed in Table 4. The planning horizon is divided into month. At each rotation schedule, each area adopted at least one fallow period and one green manure crop. The proposed model can be solved in less than a minute and includes 1998 variables and 23049 linear constraints.

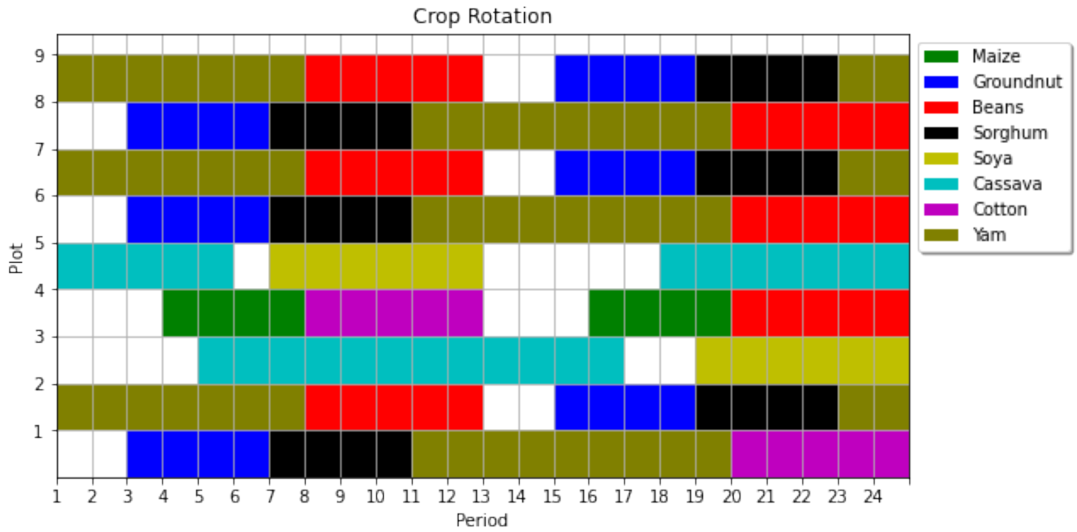


Figure 1: Illustration of crop rotation schedule proposed from the model without the addition of nutrients. The white cells represents fallow period. Yam is cultivated in $T = 23$ and ended-up in $T = 7$ of the following year on plot $j = 2$ for a total duration of 9 months $Z_{yam} = 9$. As Groundnut and Beans are from the same botanical family, there is a fallow period of 2 to avoid an immediate succession.

5.2. Study cases

The proposed model will be evaluated in two scenarios. Firstly, we present the impact of including nutrient amendment in the crop rotation schedule on the net profit (Instance 1). We evaluate the income and crop rotation schedule in this experiment, taking into consideration whether or not soil amendments are present. Besides, we present the alteration of the design of the plots on the establishing region which restricts the crop allocation. Then, we evaluate our model using a variety of two, three, and four years planning horizons (Instance 2).

5.2.1. Instance 1

Table 4 presents details about the crop, planting and harvest times and Nitrogen, Phosphorus and Potassium requirement for each crop . In this study, there are a total of eight crops (N = 8) and five families of crops (Nf = 5). Our planning horizon is two years, divided into 24 periods (T = 24). Table 5 describes the adjacency among plots and the cultivable area of each plot. We do not take into consideration the main diagonal, but the other positions in the table filled in Green represent the plots that are adjacent to each other. Details such as number of variables and linear constraint about the two models are displayed in Table 3.

Table 3
Variables and Linear Constraints of each model

Models	Variables	Linear Constraints
Without Nutrient Amendment	1944	22995
With Nutrient Amendment	1998	23049

In the first instance of our problem, the solver reached the value of the objective function in **9,66** seconds for the model without nutrient amendments which is **30,639,998 XOF** and in **61,21** seconds for the model with nutrient amendments which is **22,087,660 XOF**. Planning is presented differently in each model. The representation of the CBC solver-derived solutions for the two models is depicted in Figures 1 and 2. Figures 1 and 2 both demonstrate compliance with the adjacency constraint.

Table 4
Crop's attributes: seeding, harvesting and Nutrient Demand.

Index	Crops	Botanical Family	Sowing	Harvest	Cycle(Month)	N(kg/ha)	P(kg/ha)	K(kg/ha)
1	Maize	Poaceae	April-May-September	(July-August)-December	4	27-34	10-12	26-37
2	Groundnuts	Fabaceae	March	June	4			
3	Beans	Fabaceae	July-August	October-November	4	69	19	51
4	Sorghum	Poaceae	Mid-June-Mid-July	September-October	4	33	10	34
5	Soya	Fabaceae	Mid-June-Mid-July	November-December	6	67-71	16-26	18-53
6	Cassava	Euphorbiaceae	June-July	June-July	12	2-6	1-2	1-9
7	Cotton	Malvaceae	July-August	November-December	5	120-214	43-86	87-223
8	Yam	Dioscoreaceae	November-March-April-May	July-November-December-January	9			

Table 5
Plot's Adjacency matrix corresponding to the given farm.

Plots	Plot 1	Plot 2	Plot 3	Plot 4	Plot 5	Plot 6	Plot 7	Plot 8	Plot 9	Area in ha
Plot 1										2
Plot 2										3
Plot 3										1
Plot 4										1
Plot 5										2
Plot 6										3
Plot 7										2
Plot 8										1
Plot 9										3

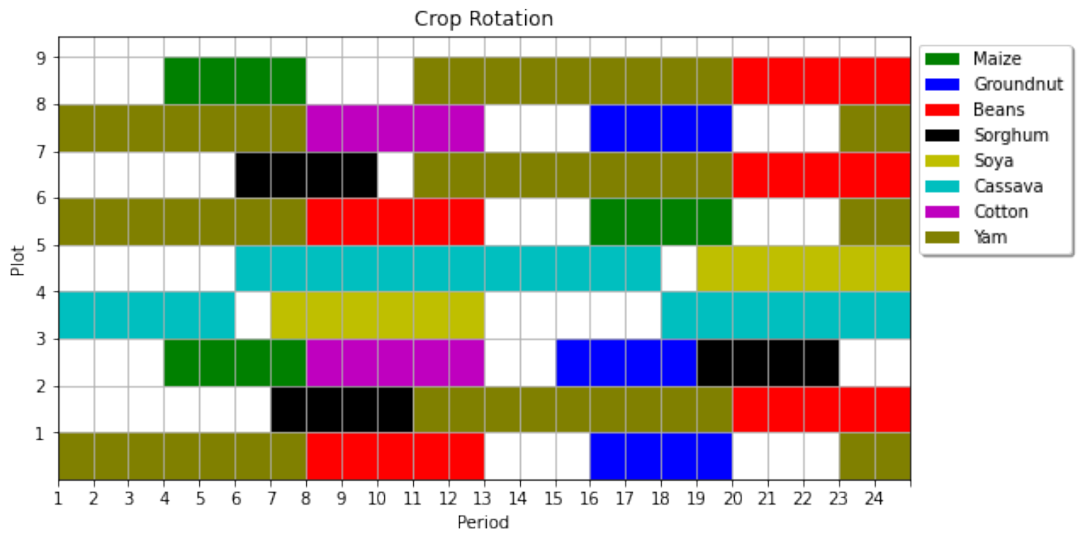
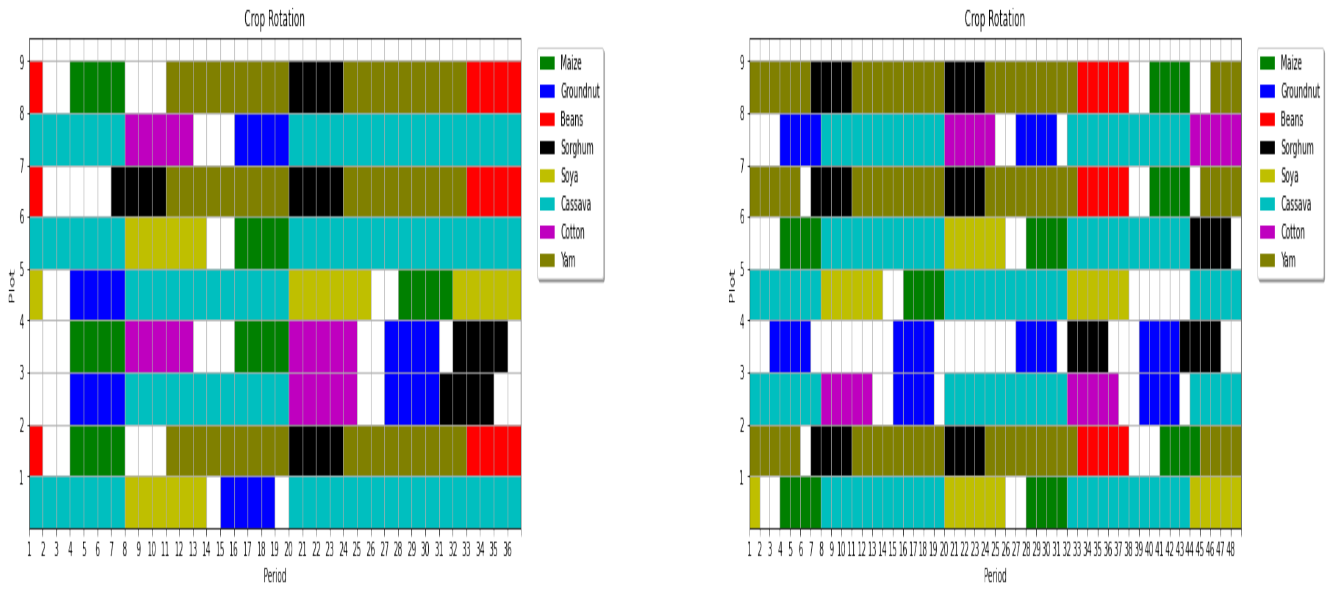


Figure 2: Illustration of crop rotation schedule proposed from the model including soil nutrients amendments. The white cells signify fallow periods. Yam is cultivated in $T = 23$ and ended-up in $T = 7$ of the following year on plot $j = 1$ for a total duration of 9 months $Z_{yam} = 9$. As Groundnut and Beans are from the same botanical family, there is a fallow period of 2 to avoid an immediate succession.

5.2.2. Instance 2

For instance 2, we want to compare the net returns from the crop rotation planning so we consider for experiment two-year, three-year and four-year period for the horizon of planning with the same crop



(a) Illustration of crop rotation schedule proposed from the model with a planning horizon of three years.

(b) Illustration of crop rotation schedule proposed from the model with a planning horizon of four years

Figure 3: Illustration of the crop schedule according to the planning horizon of three and four years respectively 36 and 48 periods

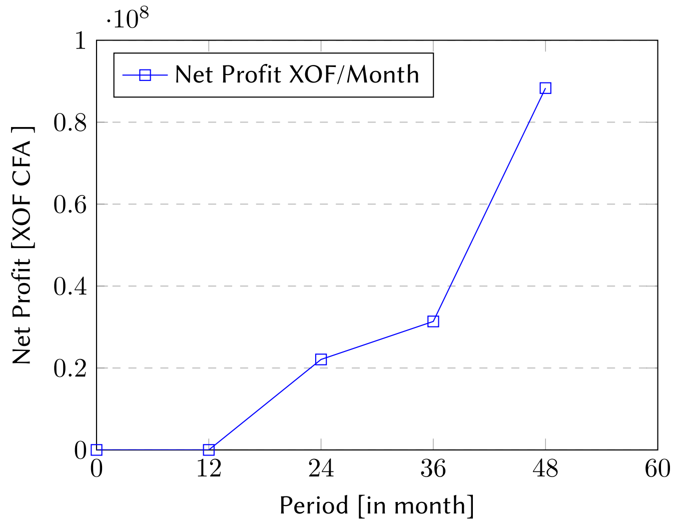


Figure 4: Variation of net profit based on planning Horizon

data as Table 4 . The Cbc solver respectively a value of **31.366.080 XOF** and **88.327.840 XOF** after **30 seconds** and **28 seconds** of running time, and the associated rotation for each plot is given in Figure 3.

As can be seen in Figure 4, the net profit increases with the planning horizon. This necessitates consideration of the horizon selection and crop selection for the rotation. But planning crops ahead of time over several years can be risky because there are many things that can affect market demand, like the weather, and market prices can change a lot from season to season.

6. Conclusions

This article highlights the significant role of legumes in modeling a crop rotation system, considering constraints such as contiguity and the use of mineral fertilizers for soil amendment. To address the problem of increasing the net income of farmers in a crop rotation system, We used a mixed integer linear programming model (MILP). Our model proposes the best possible solution by maximizing the objective, in this case farmers' income, while respecting a set of constraints, such as crop rotation rules. The best solution of the proposed model was tested in an experiment conducted for a medium-sized real plantation area with nine plots, considering eight crops from five botanical families and a two-year plantation rotation. The results of the study indicate that farmer's incomes improve when a longer planning period is considered.

However, the solutions proposed by MILP may lack the flexibility to adapt to rapid changes in the field, such as a sudden drought or market price fluctuations. This aspect will be taken into consideration in our future work by introducing a model based on stochastic linear programming model. Additionally, integrating a dynamic subdivision could further boost farmers' incomes.

Declaration on Generative AI

Either:
The author(s) have not employed any Generative AI tools.

References

[1] U. Nations, Population, ???? URL: https://www.un.org/en/global-issues/population.

[2] Proceedings of the expert meeting on how to feed the world in 2050: 24-26 june 2009, fao headquarters, rome, FAO, Rome, 2009. OCLC: 458810459.

[3] C. L. Mohler, S. E. Johnson, Natural Resource, Agriculture, and Engineering Service (Eds.), Crop rotation on organic farms: a planning manual, number 177 in NRAES, Natural Resource, Agriculture, and Engineering Service (NRAES) Cooperative Extension, Ithaca, NY, 2009. OCLC: ocn320131151.

[4] J. Zhao, Y. Yang, K. Zhang, J. Jeong, Z. Zeng, H. Zang, Does crop rotation yield more in china? a meta-analysis, Field Crops Research 245 (2020) 107659. URL: https://www.sciencedirect.com/science/article/pii/S0378429019307464. doi:https://doi.org/10.1016/j.fcr.2019.107659.

[5] L. Santos, P. Michelon, M. Arenales, R. Santos, Crop rotation scheduling with adjacency constraints, Annals OR 190 (2011) 165–180. doi:10.1007/s10479-008-0478-z.

[6] I. Fikry, M. Gheith, A. Eltawil, A new mathematical model for the deterministic crop rotation planning problem, in: 2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE, Macao, Macao, 2019, pp. 314–318. URL: https://ieeexplore.ieee.org/document/8978672/. doi:10.1109/IEEM44572.2019.8978672.

[7] N. R. Ong, M. A. R. Castro, P. S. Osorio, J. G. D. Tycangco, A. M. F. Umali, Application of mixed integer linear programming approach on crop rotation practices in organic farms in central luzon and calabarzon, philippines, Journal of Physics: Conference Series 1529 (2020) 032050. URL: https://iopscience.iop.org/article/10.1088/1742-6596/1529/3/032050. doi:10.1088/1742-6596/1529/3/032050.

[8] I. Fikry, A. Eltawil, M. Gheith, A robust crop rotation optimization model with water scarcity and net return uncertainty considerations, IEEE Access 9 (2021) 128938–128950. URL: https://ieeexplore.ieee.org/document/9539176/. doi:10.1109/ACCESS.2021.3113125.

[9] J. L. E. K. Fendji, C. T. Kenmogne, D. J. Fotsa-Mbogne, A. Förster, Improving farmers' revenue in crop rotation systems with plot adjacency constraints in organic farms with nutrient amendments,

Applied Sciences 11 (2021) 6775. URL: https://www.mdpi.com/2076-3417/11/15/6775. doi:10.3390/app11156775.

[10] B. Miranda, A. Yamakami, P. Berbert, A new approach for crop rotation problem in farming 4.0, 2019, pp. 99–111. doi:10.1007/978-3-030-17771-3_9.

[11] A. Aliano Filho, H. de Oliveira Florentino, M. V. Pato, S. C. Poltroniere, J. F. da Silva Costa, Exact and heuristic methods to solve a bi-objective problem of sustainable cultivation, Annals of Operations Research 314 (2022) 347–376. URL: https://link.springer.com/10.1007/s10479-019-03468-9. doi:10.1007/s10479-019-03468-9.

[12] I. Fikry, M. Gheith, A. Eltawil, An integrated production-logistics-crop rotation planning model for sugar beet supply chains, Computers & Industrial Engineering 157 (2021) 107300. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360835221002047. doi:10.1016/j.cie.2021.107300.

[13] K. Kokou, ANALYSE ET MODELISATION DE L'EVOLUTION DES INDICATEURS DE LA FERTILITE DES SOLS CULTIVES EN ZONE COTONNIERE DU TOGO, Ph.D. thesis, UNIVERSITE DE BOURGOGNE - FRANCE UNIVERSITE DE LOME- TOGO, 2011.

[14] A. A. El Adoly, M. Gheith, M. Nashat Fors, A new formulation and solution for the nurse scheduling problem: A case study in Egypt, Alexandria Engineering Journal 57 (2018) 2289–2298. URL: https://linkinghub.elsevier.com/retrieve/pii/S111001681730282X. doi:10.1016/j.aej.2017.09.007.

[15] L. M. R. dos Santos, P. Michelon, M. N. Arenales, R. H. S. Santos, Crop rotation scheduling with adjacency constraints, Annals of Operations Research 190 (2011) 165–180. URL: http://link.springer.com/10.1007/s10479-008-0478-z. doi:10.1007/s10479-008-0478-z.

[16] A. Filho, H. Florentino, M. Pato, A genetic algorithm for crop rotation, ICORES 2012 - Proceedings of the 1st International Conference on Operations Research and Enterprise Systems (2012) 454–457.

[17] C. Céspedes-León, S. Espinoza, V. Maass, Nitrogen transfer from legume green manure in a crop rotation to an onion crop using 15 n natural abundance technique, Chilean Journal of Agricultural Research 82 (2022) 44 – 51. doi:10.4067/S0718-58392022000100044.