Improving Farmers’ Revenue in Crop Rotation Systems with Plot Adjacency Constraints in Organic Farms with Nutrient Amendments

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Abstract: The search for sustainable agriculture is leading many economies to turn to crop rotation systems and to abandon monoculture systems which generally require increased use of pesticides and synthetic fertilizers. But the optimization of crop rotation remains a challenge, especially when considering organic farming. This work tackles the optimization of crop rotation in traditional organic farms with plot adjacency constraints and nutrient amendments. In the present configuration, each farmer owns a certain quantity of rudimentary equipment and a number of workers, all considered as resources. Farms are subdivided into plots and each plot allows only one crop at a given period. At a given interval of time, each plot receives a certain quantity of nutrient. The generated rotations are of fixed durations for all plots and the objective is to maximize farmers’ income. A linear programming approach is used to determine the solution of the proposed farming model. Three levels of constraints are combined in the linear program to generate realistic rotations: (i) biophysical constraints including crop succession and plot adjacency; (ii) structural constraints including budget and resources; (iii) organizational constraints such as nutrient amendment and market demand. To evaluate the performance of the model, scenarios based on real-world data has been defined and solved using free solvers. The solutions obtained indicate that all the constrains are satisfied. In addition, farmers’ revenue is improved, reaching a stationary position when the quantity of available resources is equal or greater than the quantity of required resources. Finally, Cbc solver is faster than GLPK solver; and it provides solutions on larger instances where GLPK does not.

Keywords: crop rotation; organic farming; adjacency constraints; nutrient amendment; integer linear programming

1. Introduction

Increasing health and environmental concerns [1], combined with the increase in the need for food due to the growth of the world population, has led to the search for sustainable agricultural systems. Sustainable agriculture does not mean going back to pre-industrial revolution methods, but rather using soil and water conservation practices with an emphasis on crop rotation that preserves productive resources by using local inputs and organic methods for plant nutrition [2].

Crop rotation is defined as the practice of growing a sequence of crops on the same land, cycle after cycle [3]. It is characterized by cycle periods, meaning we can loop, in
contrast to crop sequence which is limited to the order of appearance of crops on the same plot of land during a fixed period [4]. The main feature of such a system is crop diversification which increases yields and the use of productive resources. For instance, crop rotation can increase the yield by 38% when compared with continuous monoculture practices according to [5]. In addition, crop diversification also reduces the vulnerability of farmers to market price variability and provides a wide variety of foods to the population [6].

The concept of crop rotation highlights the problem of determining the cropping plan at the spatial and temporal levels respectively, which in most cases boils down to the choice of crops and their assignment to plots [7]. Not all crop sequences are suitable for sustainable farming. Moreover, not all crop sequences have the same economic performance, meaning that they cannot all optimize the revenue of the farmer at the end. Therefore, the need to obtain optimal crop sequences or rotation is crucial. Several techniques have been introduced in the literature, including decision trees [8], decision support systems [9], fuzzy logic [10] and mathematical programming models.

One technique identified in mathematical programming usually adopted for the development of crop rotation systems is linear programming models [11–15]. The typical problem of agricultural production planning is to determine the set of crops and the area to be allocated to each crop. Some models available in the literature are based solely on financial objectives such as profit maximization or cost minimization [11,15,16], while others are based on agricultural sustainability such as the minimization of pest proliferation throughout the planting area [10,17,18] or environmental health [13,19,20]. In the models developed in [11,15,21], the planting period is annual, and they do not take into account the subdivision of land into plots as well as the adjacency constraints. In fact, agronomic and ecological studies [22,23] demonstrate that planting plot sequence with crops of different botanic families can reduce the resources available to pests. Consequently, their population will also reduce, and their damage will be limited. Plot adjacency constraints have been considered in [24] but authors did not take into account the impact of nutrients, or production activities on crop succession and crop yield. These crop rotation approaches provide an insight into the potential organization of an agricultural system, but they are still limited. The difficulty in developing a realistic crop rotation is the large number of factors involved in the decision-making process, the relationships between these factors, and the lack of farmers’ control over some of these factors [15].

The constraint-based farm planning model presented in this paper, targets on one hand the management of the farm divided into adjacent plots, the impact of the agricultural production activities defined by data on operations, crops, and crop families to generate an optimal yield based on expert data and farmer inputs. On the other hand, it considers the nutrient amendment on the plots, the management of resources (labour, equipment) which are usually limited in traditional farms, and the demand for agricultural products throughout the year based on historical data in the areas of exploitation. The formalism represents in a generic way the farmer needs, the state of their farms and the limitations to which they are subject, and which must be considered in the crop rotation process. The proposed mathematical model therefore aims to identify the best possible crop rotation that will optimize farmers’ incomes while satisfying plot adjacency constraint as well as essential biophysical, structural, and organizational constraints including minimum nutrient requirements. The representation of crop successions is made according to the requirements and behaviours of crop families. Due to some parameters such as weather conditions or market prices that may change significantly from a season to the next, it is risky to plan crops several years in advance [2]. Therefore, the planning period in this paper is limited to 24 months.

The rest of the paper is organised as follow. Sections 2 and 3 discuss factors related to crop yield and pose a definition of the problem, respectively. Section 4 proposes a mathematical model to determine crop rotations that optimize farmers’ incomes. Section 5 presents the tools used to evaluate the mathematical model and discusses the results. This paper ends with a conclusion and perspectives for future work.
2. Crop Yield

Crop yield is a measure of agricultural production per unit area, usually in kilograms or tons per hectare [25]. This measure fluctuates according to several parameters, among which are the soil quality and the agricultural practices. Maintaining and improving soil quality and using suitable agricultural practices in continuous cropping systems are essential to maintain agricultural productivity and environmental quality for future generations [19]. For this reason, the evaluation of soil quality and farming practices is mandatory to ensure stable and optimal farm income.

2.1. Soil Quality

Physical, chemical, and biological indicators are used to assess soil quality. A set of general indicators of soil quality has not yet been defined, mainly because of the difficulty of defining and identifying what soil quality is and how it can be measured [26]. Nevertheless, a good starting point is to draw up a list of measurable soil indicators, which define the main functioning processes in the soil and ensure that the measurements we make reflect the conditions as they exist in the field. The list of indicators includes different nitrogen forms, organic matter content, soil pH, the erosion degree, and the infiltration properties.

Indicators such as erosion and their impact on crops are not easily predictable or controllable. In contrast, other important indicators are not only predictable, but also have a large long-term impact and can be addressed in a palliative manner. Among those indicators, nitrogen, phosphorus, and potassium levels are the keys to plant growth. It is therefore of great interest to understand the essential processes of these minerals and to define in more detail the means for highly productive and environmentally friendly agriculture.

An assessment of nutrient amendments, consumption and balances in the environment provides useful practical information on the evolution of nutritional status (maintained, accumulated, or depleted). It provides information about the efficiency level of fertilizer use in terms of quantity absorbed by the crop. This can help to prevent nutrient deficiencies that can be disastrous for plants. Table 1 gives the nutrient consumption of some popular crops in sub-Saharan where traditional agriculture is mainly practiced [4]. From the Table 1, tomato and onion are among the crops that consume a smaller quantity of nitrogen. Table 2 indicates the maximum annual nitrogen rate per hectare in fertilizer equivalent for some crops [27]. However, since we are dealing with organic farms, part of the mineral fertilizer should be replaced by residual organic matter. Nitrogen supply using organic amendments to crops is usually expressed in the amendment’s Nitrogen Fertilizer Replacement Value (NFRV) [28], also called the Mineral Fertilizer Equivalent [29]. NFRV is usually expressed in terms of the quantity of mineral fertilizer N that is substituted by an amount of organic amendment N (kg/kg) while obtaining the identical crop yield [30]. Depending on the soil and the source of manure, the NFRV of Mineral Concentrate (MC) can reach more than 80% [31].

Table 1. Nutrient consumption of some popular crops (in Kg/ton).

| Crop    | Nitrogen | Phosphorus | Potassium |
|---------|----------|------------|-----------|
| Cabbage | 3.5      | 1.3        | 4.2       |
| Carrot  | 3.9      | 1.7        | 6.6       |
| Onion   | 2.7      | 1.3        | 3.9       |
| Tomato  | 2.8      | 1.3        | 3.8       |

Table 2. Maximum annual nitrogen rate per hectare in fertilizer equivalent (in Kg/ha).

| Crop    | Nitrogen |
|---------|----------|
| Cabbage | 240      |
| Carrot  | 120      |
| Onion   | 120      |
| Tomato  | 420      |
2.2. Agricultural Practices

Agricultural practices are defined as a series of interdependent protocols that apply to crops and soils and whose aim is to obtain the highest yield from a crop and to ensure the viability of crop production in some conditions of an agro-ecological area. They define the activities to follow at each stage of the crop production process. For any given agricultural production system, the definition of certain agricultural production activities allows at any point in the production process to adjust the way of cultivating in response to changing circumstances such as the climate. Implementing these agricultural production activities requires prior knowledge, planning, measurement, and data recording to achieve production, safety, and sustainability goals.

3. Problem Definition

The decision to plan a cropping sequence considers many aspects, such as market opportunities, soil characteristics and resources (labor or equipment). Crop planning for large periods needs to be carefully considered and ensure stability, without compromising the benefits due to short-term changes in the agri-food industry [32].

The challenge in developing a crop rotation system is to achieve crop planning on agricultural land while taking into account the main factors that affect crop yields. The objective is to maximize the farmer incomes subject to constraints related to plot conditions, resource availability, crops characteristics and demand. The following constraints are considered in the proposed model.

- Succession of crops from the same botanical family on the same plot is not recommended [24]. This problem is mainly due to the fact that crops of the same family have similar nutrient requirements and defects (risk of contracting the same diseases or hosting the same weeds). This compromises the sustainability of the cropping system.
- Two crops of the same botanical family should not be sown at the same time on two adjacent plots [24]. This problem is again due to the fact that crops of the same family share common traits. Thus, sowing them on two adjacent plots at the same time is equivalent to sowing the same crop on these two plots. This increases the resources available for pests and consequently their population and the possible related damage they can produce.
- Budgetary constraints: this constraint limits the cost related to crop planning. In fact, the growing of each crop induces costs mainly related to intrants and material required for production activities.
- Constraints related to the use of available resources including workers: Each farmer has a set of resources including workers available to assist in farming activities. On a farm divided into plots, the allocation of resources to each crop depends on its demand. We consider that the activities related to each crop in each plot are performed simultaneously.
- Minimum Nutrient Requirements: The minimum nutrient requirement refers to the amount of soil nitrogen needed to start a crop at a given time. Here we consider the nutrient amendment of a plot as the amount of nitrogen applied to that plot during a given time interval.
- Market demand: it is an important constraint to the allocation of cash crops. This demand depends on the agricultural areas, the periods of the year and the orders placed with farmers.

4. Modelling

4.1. Revenue Maximization Model

We consider that the planting area is divided into plots. Two plots are neighbors if they share a boundary that is not reduced to a discrete set of points. For instance, if the planting area is divided into four plots, we would consider the opposite plots as adjacent.

To better understand the proposed model, the set of parameters and variables are defined in Table 3.
Table 3. List of parameters and variables.

| Parameter/Variable | Meaning |
|--------------------|---------|
| $M$                | Number of periods (in months) |
| $P_i$              | Price of crop $i$ (in XAF—currency in Central Africa) |
| $L$                | Number of plots |
| $C$                | Set of main crops (cash crops) |
| $N$                | Cardinality of $C$ |
| $NF$               | Number of botanical families |
| $F(p)$             | Set of crops of the botanical family $p$ |
| $t_i$              | Production time of the crop $i$ |
| $r$                | Variables for indexing the production time of crop $i$ |
| $Cost_l$           | Production cost associated with the use of the resource $l$ (in XAF) |
| $A[k]$             | Set of parcels adjacent to parcel $k$ |
| $l$                | Number of independent plots |
| $Z_{N_i,k}$        | Amount of nitrogen applied to plot $k$ over a time interval $a$ (in Kg/ha) |
| $S_{Ni}$           | Minimum amount of nitrogen required to start the crop $i$ (Kg/ha) |
| $B$                | Budget allocated for a production cycle (XAF) |
| $q_{ijl}$          | Quantity of resource $l$ needed for crop $i$ over period $j$ |
| $R_i$              | Crop yield $i$ (in ton) |
| $x_{ijk}$          | A decision variable that tells whether crop $i$ begins in period $j$ on the plot $k$ |
| $D_{ij}$           | Demand for crop $i$ over period $j$ (in ton) |
| $Q_l$              | Quantity of resource $l$ |
| $\alpha$           | Length of the interval $\omega$ (in month) |
| $O$                | The set of resources |
| $m$                | The cardinality of $O$ |
| $\omega$           | Number of intervals of $M$ (for amendments) |

4.2. Biophysical Constraints

The determination of a crop rotation plan for a set of plots can be limited biophysically by factors related to the biological characteristics of the crops and the physical characteristics of the soil. As biophysical constraints, we have:

- Two crops cannot be planted in the same plot [24]. In fact, a plot is entirely affected to a crop for the duration of its growing process and its harvest.

$$\sum_{i=1}^{N} \sum_{r=0}^{t_i-1} x_{i(j-r)k} \leq 1$$

(1)

With $j = 1 \ldots M$, $k = 1 \ldots L$.

- Succession of crops from the same botanical family on the same plot is not allowed [24]. This problem is mainly due to the fact that crops of the same family have similar nutrient requirements and defects (risk of contracting the same diseases or hosting the same weeds). This compromises the agronomic sustainability of the cropping system.

$$\sum_{i \in F(p)} \sum_{r=0}^{t_i} x_{i(j-r)k} \leq 1$$

(2)

With $p = 1 \ldots NF$, $j = 1 \ldots M$, $k = 1 \ldots L$.

Constraint (2) limits the sum of all crops $i$ of botanical family $p$ over their production period to a maximum of one crop.

- Two crops of the same botanical family should not be planted at the same time on two adjacent plots [24,33]. This problem is also due to the fact that crops of the same family share common attributes. Thus, planting them on two adjacent plots at the same time is equivalent to planting the same crop on both plots, which does not optimize the optimal distribution of crops on the different plots.
\[ \sum_{i \in F(p)} \sum_{r=0}^{l_i} \sum_{u \in A[k]} x_{i(j-r)u} \leq 1 \left( 1 - \sum_{i \in F(p)} \sum_{r=0}^{l_i} x_{i(j-r)k} \right) \] (3)

With \( k = 1 \ldots L, j = 1 \ldots M \).

Constraint (3) states that the number of crops from a botanical family \( p \) during their periods of production on the set of plots \( A[k] \) adjacent to a plot \( k \) must be equal to 0 if a crop \( i \) of the same botanical family \( p \) is already sown on plot \( k \). Otherwise, the number of crops is at most equal to the number of independent plots.

### 4.3. Structural Constraints

The areas allocated to cash crops are limited by structural constraints, which are mainly the availability of resources. Two types of structural constraints are considered.

- **Budgetary constraints**: this is a common constraint that limits the cost of the expenses related to crop planning to a specific budget.

\[ \sum_{i=1}^{n} \sum_{j=1}^{M} \sum_{k=1}^{L} \sum_{l=1}^{m} q_{ijl} \cdot \text{Cost}_{l,i} \cdot x_{ijk} \leq B \] (4)

Constraint (4) stipulates that the cost of resources used for all crops on all plots must not be greater than the budget.

- **Constraints related to the use of equipment and available labour**: in traditional agriculture, each farmer has a set of equipment and a given number of workers to help him in his agricultural activities.

\[ \sum_{i=1}^{n} \sum_{j=1}^{L} \sum_{k=1}^{L} q_{ijl} \cdot x_{ijk} \leq Q_l \] (5)

With \( j = 1 \ldots M, l = 1 \ldots m \).

Constraint (5) limits the amount of resource \( l \) needed for growing crop \( i \) during a period \( j \) on all plots to the available quantity. Here, the use of resources for any activity is considered for a single period, so that at the beginning of each period the amount of material available is always the same.

### 4.4. Organizational Constraints

To obtain crop rotations that are sustainable and close to the reality, a last class of constraints related to crop production activities (CPA) should be considered. This last class includes the minimum nutrient requirement for crops production and the demand on the market that can limit the production of some particular crops.

- **Minimum Nutrient Requirements**: The minimum nutrient requirement refers to the amount of soil nitrogen needed to start a crop at a given time. Here we consider the nutrient amendment of a plot as the amount of nitrogen applied to that plot during a given time interval. Let \( \alpha \) be the size of the interval adapted to the seeding of crop \( i \), has the interval during which the amendment \( Z_{N,k} \) is made, and \( S_{NI} \) its minimum required nutrient amount. Thus, on plot \( k \), at each amendment interval, \( S_{NI} \) must not be greater than \( Z_{N,k} \).

\[ \sum_{i=0}^{n} \sum_{j=\omega(a-1)+1}^{\omega a} S_{NI} \cdot x_{ijk} \leq Z_{N,k} \] (6)

With \( k = 1 \ldots L, j = 1 \ldots M, \alpha = 1 \ldots M/\omega \).

Constraint (6) can be extended to other nutrients (phosphorus and potassium).
Market demand: Market demand is another important constraint, especially when dealing with cash crops. In this formulation, the demand of a crop $i$ depends on the period $j$.

$$\sum_{k=1}^{L} R_i x_{ijk} \leq D_{i(j+t_i)}$$  \hspace{1cm} (7)

With $j = 1 \ldots M, i = 1 \ldots N$.

Constraint (7) limits the expected yield of crop $i$ sown in period $j$ on all plots in the farm to the estimated demand for that crop in period $j + t_i$. We consider here that the farmer should not exceed the estimated demand to avoid problems such as long storage or conservation of products that can generate additional costs and increase the risk of income variability.

The proposed model encompasses the concepts of crop demand, resource availability and nutritional status presented earlier. The complete model is presented below.

Maximize $Z = \sum_{k=1}^{L} \sum_{i=1}^{n} \sum_{j=1}^{n} P_i R_i x_{ijk}$  \hspace{1cm} (8)

Subject to Equations (1)–(7).

5. Evaluation

5.1. Tools

For the evaluation of the proposed model, we choose the Julia programming language. Julia has its own language for modelling linear problems called JuMP. We selected two free solvers: GLPK (GNU Linear Programming Kit) [34] and Cbc (COIN-OR Branch and Cut Interface) [35]. They have been selected since they do not require a license unlike Cplex and Gurobi.

GLPK is a solver written in the C programming language and organized as a callable library. It is a set of algorithms used to solve Linear Optimization Problems (LP), Mixed Integer Problems (MIP) and other related problems. The two main algorithms implemented in the GLPK solver are the revised ordinary simplex for linear problems and the Gomory’s cuts for linear integer problems.

Cbc is an open-source mixed integer programming solver written in C++. It can be used as a callable library or as a standalone executable. It can be called by AMPL (native), GAMS, MPL (by the CoinMP project) and JuMP. The algorithm used by Cbc to solve linear integer problems is Branch and cut for linear programming (LP) problems.

5.2. Case Studies

Several scenarios have been defined to evaluate the proposed model. Firstly, we present the impact of the availability of resources along with the length of the rotation since the crops are cultivated simultaneously (Scenarios 1 to 3). We consider tools used in traditional agricultural such as hoe and machete, like in [36]. Secondly, we present the modification of the layout of the plots on the planting area which limits the crop allocation. In fact, depending on the subdivision of the planting area, the number of independent plots can increase or decrease, influencing therefore the number of crops from the same family that can be grown simultaneously. Table 4 presents details of the planning problem for each scenario and Table 5 presents the plot adjacency matrix. In the plot adjacency matrix table, the boxes in blue represent plots that are adjacent to each other and the boxes in black represent plots that are independent from each other (meaning they do not share an efficient boundary). Each grey box represents the same plot. The nutrient amendment distributed by time interval on each plot is given in Table 6. Due to the lack of statistical data, demand estimations are simulated based on quantification of fruit and vegetable production and trade in Cameroon [37], and prices of crops adapted from [38].
Table 4. Details of the planning problem for each case.

| Case 1 | Case 2 | Case 3 |
|--------|--------|--------|
| Period | 12     | 15     | 24     |
| Plot   | 4      | 4      | 4      |
| Crop   | 4      | 6      | 6      |

Table 5. Adjacency matrix corresponding to the given farm, with blue cells indicating adjacent plots and black cells non-adjacent plots.

| Plot 1 | Plot 2 | Plot 3 | Plot 4 |
|--------|--------|--------|--------|
| Plot 1 |        |        |        |
| Plot 2 |        |        |        |
| Plot 3 |        |        |        |
| Plot 4 |        |        |        |

Table 6. Nutrient amendments on plots in Kg/ha.

| Interval 1 | Interval 2 | Interval 3 | Interval 4 |
|------------|------------|------------|------------|
| Plot 1     | 150        | 90         | 58         | 85         |
| Plot 2     | 90         | 100        | 80         | 90         |
| Plot 3     | 70         | 98         | 110        | 105        |
| Plot 4     | 130        | 95         | 115        | 75         |

Unfortunately, the result cannot be compared to [24], since objective functions are different and new constraints related to nutrient amendments and resources.

5.2.1. Scenario 1

Table 7 gives the list of crops used in the first scenario, their botanical family and production time. However, the sowing period of each crop has been ignored since favorable conditions, mainly the water quantity to grow a particular crop can be provided using an irrigation system, as it is done in the Local Development Support Programme where tomatoes and onions are grown throughout the year thanks to the irrigation system (The Local Development Support Programme is implemented by Concern Universal with Irish Aid funding. https://www.irishaid.ie/stories-of-progress/casestudies/archive/2013/september/irrigation-extending-the-growing-season/, accessed on 10 July 2021).

Table 7. Sample of the crops used in Scenario 1 with their botanical family and cultivation duration.

| Crop   | Botanical Family | Duration (Months) |
|--------|------------------|-------------------|
| Broccoli | Brassicaceae     | 5                 |
| Cabbage  | Brassicaceae     | 4                 |
| Carrot   | Umbelliferae     | 2                 |
| Tomato   | Solanacea        | 3                 |

For the first example of our problem, both solvers have reached the same value of the objective function which is 259,500,000 XAF with two different planning. Figures 1 and 2 illustrate the representation of the solutions obtained using the two solvers. Cbc provided a solution after 10 s of running, while GLPK took 10 min. The adjacency constraint is satisfied in both Figures 1 and 2. In addition, cabbage (from the same family with broccoli) is not cultivated to satisfy biophysical constraints.
Table 7. Sample of the crops used in Scenario 1 with their botanical family and cultivation duration.

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Figure 1. Representation of the solution obtained by GLPK for Case 1. On the first plot, tomato is cultivated twice and carrot once. On the second plot, Broccoli, tomato, and carrot are cultivated once. On the third plot, carrot is cultivated twice and tomato once. On the last plot, broccoli and carrot are cultivated once.

Figure 2. Representation of the solution obtained by Cbc for Case 1. Tomato is cultivated once on each plot. Carrot is cultivated once on plots 1, 3 and 4, and twice on plot 2. Broccoli is cultivated once on plots 1 and 3.

Figure 3 presents the variation of the income according to the availability of resources in scenario 1. Only three types of resources are considered. The expression [2,1,0] means we have two resources of type 1, one resource of type 2, and no resource of type 3. An obvious observation is that the income is increasing with the availability of resources, as far as the quantity of required resources is greater than the available resources. This is justified by the fact that the limitation in terms of quantity of resources limits the set of crops that can be grown simultaneously. However, the income becomes stationary when the quantity of available resources is equal or greater than the quantity of required resources. This is justified by the fact the limitation is no longer due to the quantity of resources, but to the size of the total planting area.

5.2.2. Scenario 2

This second scenario considers a period of 15 months and six crops coming from four botanical families as indicated in Table 8. Details about crops are given in Table 5. Only
we have two resources of type 1, one resource of type 2, and no resource of type 3. An obvious observation is that the income is increasing with the availability of resources, as far as the quantity of required resources is greater than the available resources. This is justified by the fact that the limitation in terms of quantity of resources limits the set of crops that can be grown simultaneously. However, the income becomes stationary when the quantity of available resources is equal or greater than the quantity of required resources. This is justified by the fact the limitation is no longer due to the quantity of resources, but to the size of the total planting area.

Figure 3. Variation of income according to the availability of resources in scenario 1.

5.2.2. Scenario 2

This second scenario considers a period of 15 months and six crops coming from four botanical families as indicated in Table 8. Details about crops are given in Table 5. Only Cbc reached an optimal value of 36,700,000 XAF after two minutes of running, with the rotation presented in Figure 4. Parsley (from the same family with broccoli) and cabbage (from the same family with carrot) are not cultivated to satisfy biophysical constraints. GLPK, on the other hand, exceeded the time limit of 12 h without finding a solution.

Table 8. Sample of the crops used in Scenario 2 with their botanical family and cultivation duration.

| Crop    | Botanical Family | Duration (Months) |
|---------|------------------|-------------------|
| Broccoli | Brassicaceae     | 5                 |
| Cabbage  | Brassicaceae     | 4                 |
| Carrot   | Umbelliferae     | 2                 |
| Parsley  | Umbelliferae     | 6                 |
| Tomato   | Solanaceae       | 3                 |
| Onions   | Aliacea          | 4                 |

Figure 5 presents the variation of the income according to the availability of resources in scenario 2. The same remarks with Figure 3 can be extended to Figure 5. The income is increasing with the availability of resources until the required quantity of resources is satisfied. Then, the income is stationary, due to the constant size of the total planting area.

5.2.3. Scenario 3

The third scenario considers a two-year period with six crops and four botanical families as presented in Table 8. The Cbc solver has reached a value of 57,040,000 XAF after three minutes of running time, and the associated rotation for each plot is given in Figure 6. Unfortunately, the GLPK solver again exceeded the time limit of 12 h without finding a solution.
Cbc reached an optimal value of 36,700,000 XAF after two minutes of running, with the rotation presented in Figure 4. Parsley (from the same family with broccoli) and cabbage (from the same family with carrot) are not cultivated to satisfy biophysical constraints. GLPK, on the other hand, exceeded the time limit of 12 h without finding a solution. Figure 5 presents the variation of the income according to the availability of resources in scenario 2. The same remarks with Figure 3 can be extended to Figure 5. The income is increasing with the availability of resources until the required quantity of resources is satisfied. Then, the income is stationary, due to the constant size of the total planting area.

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| Parsley   | Umbelliferae     | 6                 |
| Tomato    | Solanaceae       | 3                 |
| Onions    | Aliacea          | 4                 |

Figure 4. Representation of the solution obtained by Cbc in scenario 2. Broccoli is cultivated once on plots 1, 2, and 3. Onion is cultivated only on plot 1. Carrot is cultivated once on plots 1 and 3, twice on plot 2, and thrice on plot 4. Finally, Tomato is cultivated once on plot 1 and 2, and twice on plot 3.

Figure 5. Variation of income according to the availability of resources in scenario 2.
Figure 6. Representation of the solution obtained by Cbc in scenario 3. Onion is cultivated once on plots 1 and 4, and twice on plots 2 and 3. Carrot is cultivated once on plot 4, thrice on plot 1 and four times on plots 2 and 3. Tomato is cultivated once on plot 3, twice on plots 2 and 4, and thrice on plot 1. Finally, broccoli is cultivated twice only on plot 4.

Figure 7 presents the variation of the income according to the availability of resources in scenario 3. The same remarks with Figures 3 and 5 are extended to Figure 7. The income is increasing with the availability of resources until the required quantity of resources is satisfied. Then, the income is stationary, due to the constant size of the total planting area.

Figure 7. Variation of income according to the availability of resources.
5.3. Impact of the Area Subdivision

The variation of the farm shape and the layout of the subdivisions defines the adjacency constraints and the number of independent plots. Figure 8 provides four layouts with different adjacency constraints. Subdivisions (a), (b), (c), and (d) in Figure 8 present respectively two, three, two, and four independent plots. In subdivisions (b) and (d), we suppose the Inter-Plot Distance (IPD) large enough to eliminate edge effect and inter-plot competition. The associated income to each subdivision is given in Figure 9.

![Figure 8. Various farm subdivisions, with no Inter-Plot Distance (IPD) in (a) and (c), and acceptable Inter-Plot Distance (IPD) in (b) and (d).](image)

![Figure 9. Change in incomes based on farm subdivisions in Figure 8.](image)
Although subdivisions (a) and (c) provide the same income, subdivision (a) may provide a larger income since it contains two sets of two independent plots: the set of blue plots and the set of black plots. From a general observation, the higher the number of independent plots, the higher the income can increase.

6. Conclusions and Future Work

This paper introduced a new modelling of realistic crop rotation system with plot adjacency constraints and soil amendments with mineral fertilizer. The model optimizes farmers’ incomes while satisfying essential biophysical, structural, and organizational constraints. The model has been evaluated using free solvers on several scenarios using different datasets and farm subdivisions. The solutions obtained indicate that all the constraints are satisfied and farmers’ revenue is improved. Cbc and GLPK solvers provide the same revenue with different rotations for small instances. But for large instances, only Cbc provide a solution in a reasonable time. Besides optimizing farmers’ revenue, this model can be an important tool for improving farm sustainability for both cash crops and subsistence agriculture.

However, the proposed model does not consider uncertainty on some parameters, such as the variability of price of a crop on the market at a particular period as well as the variability of the demand. Uncertainties related to the parameters deserve to be addressed in future work, especially in crop rotation systems that deal with a long period. The second limitation of this work is the fact that the farm is subdivided beforehand and remained static. A plot is affected to only one crop at a particular period, even if the crop does not use the total area of the plot due to a possible resource limitation. So, some plots may remain underused, and consequently limit farmers’ income. Thus, dynamic subdivision can help to improve farmers’ revenue. Finally, we can consider including cover crops in the optimization model to improve soil organic matter and fertility.

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