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Crop selection and scheduling for green production with intercropping and rotation

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Abstract. In this study, we address a crop selection and scheduling problem employing two cropping systems, crop rotation and intercropping, simultaneously on a given parcel of land. Moreover, we also consider other ecological practices such as the use of fallow and green manure. We propose a 0-1 linear programming model to maximize revenue by determining the optimal combinations of crops in space (crops to be planted as neighbors) and in time (crop rotation schedule) while meeting the yearly demand of each crop. A realistic numerical example is presented to demonstrate the performance of the model.

Keywords: Sustainable agricultural production · Crop schedule · Crop rotation · Intercropping .

1 Introduction

Conventional agricultural production systems are generally based on monoculture (i.e., growing only one crop) as this practice is generally lowest in production cost. However, monoculture often has important adverse side-effects that are not accounted for. These include the environmental costs of water contamination by pesticides and other polluting inputs, or the social costs associated with the exclusion of small farmers due to the large-scale capital requirement [5], [12]. To avoid these adverse effects, more sustainable agricultural production systems are needed that are economically profitable, environmentally safe, and socially equitable. To this purpose, several strategies based on increasing spatial and temporal crop diversification have been proposed such as intercropping (combination in space), crop rotation (combination in time), agroforestry, composting, and green manuring [14], [21].

To compete with monoculture, the proposed farming practices should be combined in such a way that fewer inputs and resources are used while yields are not drastically reduced and may even be improved. This requires thorough planning and solving complex problems where, both technical and ecological production aspects of those farming practices need to be considered.

In this study, we address a crop selection and scheduling problem employing two cropping systems, crop rotation and intercropping, simultaneously on

a given land, while considering other ecological practices such as the regular employment of fallows and green manures. Our objective is to determine the optimal combinations of crops in space (crops to be planted as neighbors) and in time (crop rotation schedule) to maximize revenue while meeting the yearly demand of each crop. We propose an integer linear programming (ILP) model to select the best combination of crops in space and time. A numerical experiment is conducted based on real crop data and an optimal crop schedule is provided to demonstrate the performance of the model.

In the next section, we first give a primer on sustainable cropping systems. In Section 3, we present the literature review and highlight the contribution of our work. In Section 4, we present the ILP formulation for our problem. Section 5 presents the numerical example followed by a conclusion.

2 Sustainable Agriculture Production Practices

Below we explain the sustainable agricultural practices that have been employed in this research. We present as well our assumptions, depending on the practical use of those practices.

Crop Rotation is the practice of planting different types of crops sequentially on the same plot of land to improve soil health, optimize nutrients in the soil, and combat pest and weed pressure [5]. It is generally undesirable to grow two crops of the same botanical family in sequence on the same piece of land to prohibit the propagation of pests [19]. Crop Rotations are most effective when combined with practices such as composting, intercropping, cover cropping, green manuring and short fallow periods [7].

Intercropping is the practice of growing two or more crops in the same field simultaneously or sequentially within the same season [5]. The key advantage of intercropping is the greater yield generated by the crop interactions. It has many other beneficial effects like increased biodiversity, nitrogen fixations by legumes, nutrient recycling in the soil, better control of pests and diseases, more efficient use of environmental sources, soil coverage and stable yields [15].

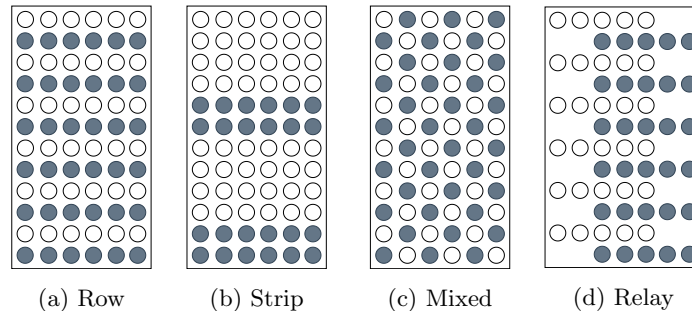


Fig. 1: Schematic illustrations of alternative intercropping systems

In this work, we limit intercropping to two crops for tractability and simplicity. There exist several types of intercropping systems. Most common ones such as mixed cropping, row intercropping, strip intercropping and relay intercropping are illustrated in Figure 1. In this work, we consider *row intercropping* where different crops are grown at the same time in the same piece of land with a distinct row arrangement [6]. Within the row layout, we also employ *relay intercropping* where intercrops were sown when the first crop reach maturity but before being harvested. We choose to work with row intercropping due to its structured layout and suitability for a large-scale farming, and relay intercropping due to the time flexibility it provides.

Green manuring is the practice of leaving uprooted or sown crop parts to wither on a field so that they serve as a mulch and soil amendment [5], [12]. The function of a green manure crop is to add organic matter to the soil, increasing the nitrogen and nutrient supply of the soil thereby increasing its productivity.

In crop rotation, crops are categorized into three groups with respect to their nutrient demand. Green manures are heavy givers that provide necessary nutrients to heavy feeders or light feeders. Since heavy feeders consume most of the nutrient in soil, in our schedule, we consider employing green manure (planting a heavy giver) after a fixed number of heavy feeders, not necessarily sequential.

Fallow is the practice of leaving the land without being sown for one or more vegetative cycles to allow the land to recover and store organic matter and reduce pest damage [5], [12].

3 Literature Review

The standard crop rotation problem is defined as determining the sequence of crops to plant, one after the other, in a given area to optimize a certain objective such as maximizing yield, profit, or minimizing area, etc. The problem is modeled as a linear program by many researchers such as [11], [8], [13], [9]. However, none of them consider environmental concerns and sustainability practices.

In the recent literature, there exists a number of studies that address the problem in a sustainable development context, taking into account environmental constraints or objectives related with increasing soil quality, reducing the use of resources, increasing diversity. [10] developed a software program called ROTAT that generates all possible rotations for a given set of crops, however, they do not optimize the rotations. Later, a group of researchers, [19], [2] focus on managing the area to be planted while satisfying the demand through reasonable crop schedules rather than optimizing the crop selection itself. [19] considered a sustainable vegetable crop demand supply problem. They determine the division of the available arable areas in plots and, for each plot, obtain an appropriate crop rotation schedule respecting ecological constraints. Their objective is to maximize the plots occupation considering demand constraints, proposing a 0-1 linear optimization model. [2] address Minimum-Space Crop Rotation Problem

(MSCRP) which is defined as constructing crop rotations to minimize the total space area required to meet demand.

[20] is the first to introduce adjacency constraints in crop rotation problem. Adjacency constraints prevent crops of the same botanical family to be cultivated at the same time in neighboring plots. They propose a 0-1 optimization model for crop rotation in different areas, with an objective again to maximize the land use subject to neighborhood and succession restrictions for crops of the same botanic family. Later, [4] adapted the model of [20] and introduced demand constraints as well as an objective function which maximizes the profit of planted crops. Recently, [16] proposed some improvements in the model presented by [20] and [4] by considering both objectives of maximizing plot occupation and the profit.

We are the first to employ two cropping systems (crop rotation and intercropping) simultaneously to determine the crop schedule. Intercropping can be considered similar to adjacency constraints, but they differ in several key ways. In [20], [4], and [16], adjacency relations are modeled as constraints which state adjacent plots cannot grow, simultaneously, crops belonging to the same botanical family. Thus, it defines strictly which group of crops cannot be planted, and ignore the yield information. This might be misleading considering that individual crops within the same family might have different effects on productivity when intercropped with a specific crop [15].

We consider both the family of crops (in determining the crop sequence) and the yield information (in determining the crops to intercrop). Additionally, intercropping involves dividing the land into many adjacent rows or strips and defines the two-way interaction between specific crops in terms of yield. Hence, our model chooses to plant the specific crops (not a family of crops) simultaneously or in sequence that have the highest positive outcome on the soil, and thus also on the yield. Moreover, [20], [4] mainly focused on determining the area used for plantation or the best division of land to meet the demand through a feasible crop schedule. They do not address finding the optimal sequence of crops to be planted in a crop rotation problem.

4 Methodology

We consider a planning horizon of $|L|$ years, where the planning time unit is one month. We assume that each crop is planted at the beginning of a month. Each crop has a production time h_i , which includes the time required to sow, grow, and harvest. Each crop also has a suitable sowing (planting) time window. To disincentivize monocropping the highest revenue crop, we assume that there is a maximum and minimum annual demand (d_{il}^{max} and d_{il}^{min}) for each crop.

C is the set of crops that can be selected for planting, including the ones for green manuring and a hypothetical crop associated with fallow. Crops are also categorized according to their nutrient demands; the sets C_f, C_v and C_g correspond to the set of heavy feeders, heavy givers and cover crops (green manure), respectively. Note that the sets C_v and C_g might contain the same crops, as heavy givers are generally also used as cover crops. However, cover

Parameters:	
S	number of rows in the land
NF	number of botanical families
p_i	price (per kg) of crop i
h_i	production time (in months) of crop i
y_i	yield (kg) of crop i when grown as a sole crop
e_{ijk}	% effect of intercropping on the yield of crop i when crop j is planted k months before or after crop i
ω	number of heavy feeders planted
d_{il}^{min}	minimum expected demand for crop i in the year l
d_{il}^{max}	maximum expected demand for crop i in the year l
Sets:	
L	set of years indexed by $l = 1, 2, \dots L $
T	set of time periods (months) indexed by $t = 1, 2, \dots T $
C	set of crops indexed by $i, j = 1, 2, \dots N$ where $i = N$ hypothetical crop associated with fallow
C_f	set of heavy feeder crops
C_v	set of heavy giver crops
C_g	set of cover crops
$C_{m(t)}$	set of crops which can be planted at each month t where $m(t) = (t - 1)_{mod(12)} + 1$
$F(\delta)$	set of crops of botanical family $\delta = 1, 2, \dots NF$
Decision Variables:	
$x_{it}^a = 1$	if crop i is planted (sown) at time t at row a, 0 otherwise
$x_{it}^b = 1$	if crop i is planted (sown) at time t at row b, 0 otherwise
$z_{ijtk}^a = 1$	if crop i is planted in row a at time t and crop j is planted next to it k months before or after, 0 otherwise
$z_{ijtk}^b = 1$	if crop i is planted in row b at time t and crop j is planted next to it k months before or after, 0 otherwise .

crops differ in terms of production time in green manure (we assume half time) and they do not have any yield as they are not harvested.

To consider intercropping effects, the arable land is divided into S number of rows, consisting of an equal number ($S/2$) of rows a and rows b . The parameter e_{ijk} models the intercropping effect on the yield which is dependent not only on the type of crops intercropped but also the timing of plantation. $x_{it}^a = 1$ ($x_{it}^b = 1$) and $z_{ijtk}^a = 1$ ($z_{ijtk}^b = 1$) are the binary decision variables described in the notation list.

The crop rotation problem consists in determining the types of crops to plant and their sequence at rows a and rows b over a finite planning horizon in order to maximize the revenue subject to ecological and demand constraints. The integer linear programming model formulation is given as:

$$\text{Maximize } \sum_{t=0}^{|T|} \left[\sum_{i=1}^N p_i y_i \left(x_{it}^a + x_{it}^b + \sum_{j=1}^N \sum_{k=-h_j+1}^{h_i-1} e_{ijk} (z_{ijtk}^a + z_{ijtk}^b) \right) \right] \quad (1)$$

subject to

$$\sum_{i \in C} \sum_{r=0}^{h_i-1} x_{i(t-r)}^\alpha \leq 1 \quad \alpha = \{a, b\} \quad \forall t \in T \quad (2)$$

$$\sum_{i \in C \setminus C_m(t)} \sum x_{it}^\alpha = 0 \quad \alpha = \{a, b\} \quad \forall t \in T \quad (3)$$

$$\sum_{i \in F(\delta)} \sum_{r=0}^{h_i} x_{i(t-r)}^\alpha \leq 1 \quad \alpha = \{a, b\} \quad \forall t \in T \quad \text{and} \quad \delta = 1, 2, \dots, NF \quad (4)$$

$$x_{it}^a + x_{j(t+k)}^b \geq 2z_{ijtk}^a \quad \forall i, j \in C, \quad \forall t \in T, \quad k = -h_j + 1, \dots, h_i - 1 \quad (5)$$

$$x_{it}^a + x_{j(t+k)}^b - 1 \leq z_{ijtk}^a \quad \forall i, j \in C, \quad \forall t \in T, \quad k = -h_j + 1, \dots, h_i - 1 \quad (6)$$

$$x_{it}^b + x_{j(t+k)}^a \geq 2z_{ijtk}^b \quad \forall i, j \in C, \quad \forall t \in T, \quad k = -h_j + 1, \dots, h_i - 1 \quad (7)$$

$$x_{it}^b + x_{j(t+k)}^a - 1 \leq z_{ijtk}^b \quad \forall i, j \in C, \quad \forall t \in T, \quad k = -h_j + 1, \dots, h_i - 1 \quad (8)$$

$$\sum_{r=0}^{t-1} \sum_{i \in C_f} x_{ir}^\alpha + x_{jt}^\alpha \leq \omega \sum_{r=0}^{t+h_j} \sum_{k \in C_g} x_{kr}^\alpha + (\omega - 1) \quad \alpha = a, b \quad \forall j \in C_f, \forall t \in T \quad (9)$$

$$\omega \sum_{r=0}^t \sum_{k \in C_g} x_{kr}^\alpha \leq \sum_{r=0}^t \sum_{i \in C_f} x_{ir}^\alpha \quad \alpha = \{a, b\}, \quad \forall t \in T \quad (10)$$

$$\sum_{r=t-6}^{t+6} (x_{Nr}^\alpha + \sum_{k \in C_g} x_{kr}^\alpha) \geq 1 \quad \alpha = \{a, b\}, \quad t = 6, \dots, |T| - 6 \quad (11)$$

$$d_{il}^{min} \leq \sum_{t=12(l-1)+1}^{12l} \left[\frac{S}{2} y_i \left(x_{it}^a + \sum_{j=1}^N \sum_{k=-h_j+1}^{h_i-1} e_{ijk} z_{ijtk}^a \right. \right. \\ \left. \left. + x_{it}^b + \sum_{j=1}^N \sum_{k=-h_j+1}^{h_i-1} e_{ijk} z_{ijtk}^b \right) \right] \leq d_{il}^{max} \quad \forall i \in C \quad \text{and} \quad \forall l \in L \quad (12)$$

In the objective function, we maximize the total revenue obtained from each crop pair throughout the planning horizon. Constraint (2) ensure that at most one crop is planted at a given time t in rows a and b . Additionally, constraints do not allow to plant any other crop during the production time (h_i) of the cultivated crop i . Constraint (3) ensure only the crops that are possible to be planted during that month are planted. Constraint (4) forbid crops of the same botanic family to be planted in sequence (immediately one after the other). Constraints (5,6) and (7,8) keep the intercropping information for the crops in rows a and rows b , respectively. Constraint (9) force a green manure after ω heavy feeders are planted in rows a and b (regardless if they are consecutive or not). Constraint (10) ensure that green manures are not done preemptively to allow successive heavy feeders greater than ω . Constraints (11) ensure that we do

Table 1: Crop Data

	Crops	Botanical Family	Nutrition Demand	Plantation Periods	Prod.time (months)	Yield (kg/row)	Price (€/kg)	Demand (min,max)
1	Onion	Allium	Light Feeder	2-3, 5-6, 8-11	4	40	160	(0, 100)
2	Coriander	Apiaceae	Light Feeder	6-7, 10-11	2	7	25000	(0, 7)
3	Beans	Fabaceae	Heavy Giver	2-3, 5-6	3	1,75	2430	(1, 100)
4	Soybeans	Fabaceae	Heavy Giver	6-7, 2-3	4	2	344	(0, 100)
5	Groundnut	Fabaceae	Heavy Giver	6, 10-1	4	2,5	1410	(0, 100)
6	Maize	Poaceae	Heavy Feeder	6-7, 10-11, 2	3	7,5	160	(0, 100)
7	Tomatoes	Solanaceae	Heavy Feeder	all year	4	55	1120	(0, 55)
8	Chilli	Solanaceae	Heavy Feeder	1-2, 5-6, 9-10	4	12,5	1700	(12, 100)
9	Eggplant	Solanaceae	Heavy Feeder	5-6, 8-9, 12-1	4	22,5	2170	(0, 25)
10	Potato	Solanaceae	Heavy Feeder	6-7, 10-11	4	20	130	(0, 100)
11	Ginger	Zingiberaceae	Heavy Feeder	2, 3, 5	6	14,08	2300	(0, 20)

either fallow (the crop N is fallow) or green manure in a 12-month rolling time intervals. The last constraint enforces the minimum and maximum demands.

5 Numerical Example

We demonstrate our model on a hypothetical tropical land based on real data as research in agro-ecology and intercropping is very popular in the regions with this climate. In our numerical example, we consider 11 crops grown in tropical regions, e.g. Brazil and India. Table 1 presents the type of crops and their parameters. The yield of sole-planted crops is obtained from FAO Statistics [1]. The price of the crops are determined based on average prices in France in 2020. Table 2 presents the percentage yield effect of intercropping one crop with another. The intercropping data is obtained through extensive literature review; some of the references are [17], [3] and [18]. A value of 0 indicates no effect, while a value of -100 denotes the crops are not compatible for intercropping and thus forbidden.

Table 2: Percentage Yield Effect (e_{ij}) of Intercropping crop $i \in C$ with $j \in C$

	1	2	3	4	5	6	7	8	9	10	11
1	0	0	-100	-100	0	-82,67	-3,22	-24,9	-75,81	-100	0
2	0	0	-100	-100	-24,74	-90,85	-73,54	0	-65,72	-100	0
3	-100	-100	0	0	-100	-58	-25	0	13	-100	27,42
4	-100	-100	0	0	-100	-13,25	0	-26,31	0	-100	0
5	0	-14,43	-100	-100	0	-55,55	0	0	-63,92	-100	-100
6	-8,84	-3,3	9,25	-20,39	-2,29	0	-13,96	-21,49	-28,51	-44,68	79,27
7	-15,16	-16,71	-3	0	0	-52,3	0	-100	-100	-100	-12,83
8	-73,51	0	0	-40	0	-42,96	-100	0	-100	-100	-100
9	-0,46	-21,58	-16,25	0	20,97	2	-100	-100	0	-100	-100
10	-100	-100	-100	-100	-100	-61,72	-100	-100	-100	0	-100
11	0	0	27,2	0	-100	-23,01	-18,64	-100	-100	-100	0

We consider a planning horizon of two years ($|L| = 2$), divided into months ($|T| = 24$). We set $\omega = 2$ to allow only two heavy feeders before forcing a green manure to heal the soil.

The model is implemented in the PuLP library for Python and solved using ILOG CPLEX 12.10. The example was run on a PC with an Intel(R) Core (TM) i7-10510U CPU @ 1.80 GHz with 16GB of RAM. The problem was solved to optimality in 2134 seconds yielding the policy in Figure 2 with an objective value of 615,797.33. Alternate shading of light and dark grey is used for successive crops with white space corresponding to nothing planted at the time. The solid black shows a forced fallow period. Green manure are diagonally hatched.

Table 1 reveals that the highest revenue per row (yield x price) comes from Coriander, Tomatoes, Eggplant, Ginger and Chilli, respectively, with Coriander almost three times the revenue of Tomatoes. The model would normally seek to plant Coriander whenever possible, however we limit it to once per year by setting its demand equal to its yield. We similarly limit Tomatoes and Eggplant to once per year by limiting their demand. To promote the planting of Chilli and Beans which have comparatively lower revenues, we set a minimum demand to be met. The example policy shows that the highest revenue crops are indeed selected as much as possible, while respecting all of their constraints regarding placement and scheduling.

Constraint (1) is obviously respected as two crops are never planted at the same time and Constraint (2) is respected by only planting crops in the period in which they are allowed. Constraint (3) is seen through the spacing (fallow) between Chilli and Eggplant and then between Chilli and Tomatoes in Row B as they are from the same botanical family and can not be planted immediately following one another. Since this is not a forced fallow due to Constraint (10), but for family scheduling purposes, it is shown as white space. Constraints (8) and (9) are respected by forcing a green manure (Groundnut_GM) after the two heavy feeders Eggplant and Chilli in Row B and again after Tomatoes and Eggplant in Row A. Constraint (10) is seen in Row A where a Fallow is forced at $t = 8$ and $t = 17$ as there is no green manure in Row A until the very end and we must have at least one fallow within any 12-month interval.

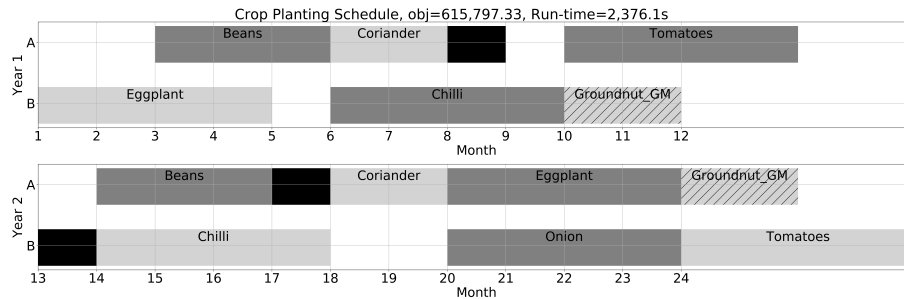


Fig. 2: Optimal Crop Schedule

A strong impact of intercropping effects can also be seen in this policy. Eggplant planted with beans will decrease its yield by 16.25%, which is unfortunate, but is chosen by the model as it is still highly desirable due to its still high revenue with respect to the other crops, and beans are required by the demand constraints. Beans will, however, receive a 13% increase in yield which will help to offset the yield loss of Eggplant. Eggplant is also forbidden to be planted with Chilli (-100 intercropping effect) which also has a minimum demand to be met. The policy is able to satisfy these intercropping constraints.

6 Conclusion and Future Work

We have formulated a 0-1 linear program to optimize crop selection and scheduling while considering ecological aspects such as intercropping and rotation. This model is an initial work in trying to promote (economically, ecologically, and socially) a combination of green agro-ecology principles in a practical way. It will be a valuable tool in moving away from destructive monoculture habits that currently widely exist in large-scale agriculture. While the model is efficient for small sizes, it quickly becomes intractable for CPLEX as the number of crops and the time horizon increases. Specialized algorithms and/or heuristics will need to be developed to solve larger instances to (near) optimality. Moreover, the structure of the policies could be studied and demonstrated to develop more efficient solution procedures.

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