

Chapter 3

EFFECT OF CROP PATTERN ON CROP YIELD -A MATHEMATICAL MODEL

The chapter outlines the cropping scenario in Rajasthan. The era before and after the Green Revolution is reviewed to determine the change in cropping pattern. A case study is being illustrated to investigate the challenges and the issues faced by farmers. A mathematical model for optimal crop-mix and crop combination is formulated.

3.1 Change in Cropping Scenario

With the adoption of Green Revolution in 1960's and 1970's country become self-reliant in terms of total crop production. The main aim of the revolution is to increase crop production by introducing High Yielding Variety (HYV) of seeds. But HYV seeds are restricted only for five crops namely- wheat, rice, sorghum (jowar), pearl millet (bajra) and maize. However, wheat is the major crop of the revolution. With the adoption of high yielding seeds approximately 10 million of buffer tonnes of grains had been harvested in a year (Singh, 2019).

Thus, authors concentrate their study to analyse the structural change in cropping scenario after Green Revolution. The era of post Green Revolution, shows a change in land-use pattern too. Benefits and outputs from revolution were experienced mainly during the era of 1965-1980's resulting in substantial increase in food grains especially wheat and rice.

With the increase in crop production and productivity the need to identify the challenges and constraints related with agriculture sector has emerged. However, during the period of Green Revolution some of the issues related to cropping pattern need improvisation. The transformation of subsistence agriculture to commercial one, makes the well-off farmers to acquire more land under cultivation making small farmers to either work as a farm laborers or shifting to some other business. Pal et al., (1992) focusses on the fact that the adoption of Green Revolution leads to the overutilization of natural resources.

Increased productivity especially of wheat during a period motivated many researchers to carry out study to analyse the impact of cropping pattern and its related factors to increase farm revenue. The farm outputs can be enhanced by optimizing unpredictable variables such as rainfall, temperature, organic matter, soil moisture and humus content. Thus, a mathematical

approach to model a farm scenario; there is a need to include the uncontrollable factors too. Kanna & Jaisree, (2015) in their study forecasted the unpredictable variables by using Ant Colony Algorithm. Minitab software is used to develop a mathematical equation of uncontrollable agriculture factors. The model formulated help the maize growers in making efficient resource allocation.

One of the benefits of Post-Green Revolution is the improved agricultural technology, that promotes high yielding variety of crop, intensive & diversified cultivation, better irrigation and cultivation techniques, reduction of post and pre-harvest losses. High yielding variety of seeds had been developed for many crop varieties but the production, productivity and operational cost depends on the type of crop and region allocated under each variety. Kumar, (1989) focuses his study to analyse the utilisation of fertilizers, productivity, production cost, farm revenues and labour cost. Presently, land-use pattern is changed to a great extent as it was at the era of Green Revolution. With this change in structure of cultivation, India's annual Gross Domestic Product (GDP) had shown a rise from US\$25 billion to US\$100 billion. During an initial phase of revolution, the growth in productivity is minimal and was largely concentrated to wheat and rice. However, in 2000-2014, GDP had risen from US\$101 billion to US\$367 billion. The growth in GDP is due to the adoption of horticulture crops, dairy and poultry.

Earlier, most of the farmers cultivate food grains as a major crop but with the adoption of technology and innovation in sector after the Green Revolution farmers were shifted to cash crops along with food grains.

3.2 Effects of Green Revolution on Cropping Pattern

The adoption of technological and mechanization system after the Green Revolution brought a paradigm shift in cropping scenario. Since, agriculture sector become modernised and technologically efficient in terms of crop variety and production both these factors made the sector more commercialized than ancient times. These changes in sector shows a positive effect by providing employment to a large population. Thus, the growth of sector due to Green Revolution, contributes to overall economic development of a country.

Green Revolution make India self-efficient in terms of crop production. The revolution had brought a paradigm shift in crop choice. Traditionally practiced crop pattern of pulses and cereals shifted to rice, maize and wheat. Multiple crop scenario become more popular along

with the cultivation of short duration crops such as coriander and cucumber. These short duration crops enhance the feasibility of the decision space.

Consequently, the expansion and commercialisation of sector strengthens the rural-urban relationship and thus, provides an aid for the smooth inflow of agri-products among all the parameters of supply chain (Pal et al., 1992). During Green Revolution (Moscona, 2019) explains the rapid growth of technology in sector to determine the impact of structural change in cropping scenario and crop productivity both in and across the globe. His study explores varying ecological parameters that investigates the impact of crop-specific technologies on productivity. The main focus of his study is to determine how growth of agricultural productivity affects the economic development. Study give two main contributions:

1. Provide an empirical analysis of agricultural productivity caused during Green Revolution.
2. Following same, identifies the techniques to estimate the impact of agricultural productivity on structural transformation.

Both the parameters mentioned above understands equilibrium effects of modern agriculture production and explains weather different analysis provides a same impact on agriculture sector. To analyse the change in agricultural production, comparison has been carried out to investigate the productivity during Green Revolution, by introducing HYV's during the period. However, due to variations in topographical and ecological parameters different regions are able to avail the benefits of revolution. These differences introduce an exogeneous variations in agricultural productivity.

Era of post Green Revolution, increased the arable land from 97.2 million hectares (in 1950) to 126.04 million hectares (in 2014) (Agricultural Statistics at a Glance 2016, 2017). A period of 1950's shows a decline in coarse cereals, sorghum and pearl millet (Fig. 3.1). On contrary, area under rice, wheat, maize, and rice increased tremendously. There is a growth of crop production particularly, rice and wheat due to the introduction of mono-hybrid crop in India. Consequently, production of pearl millet shows a decline since, focus of Green Revolution is to increase the productivity of rice and wheat mainly. Thus, millets and cereals does not show much yield during an era.

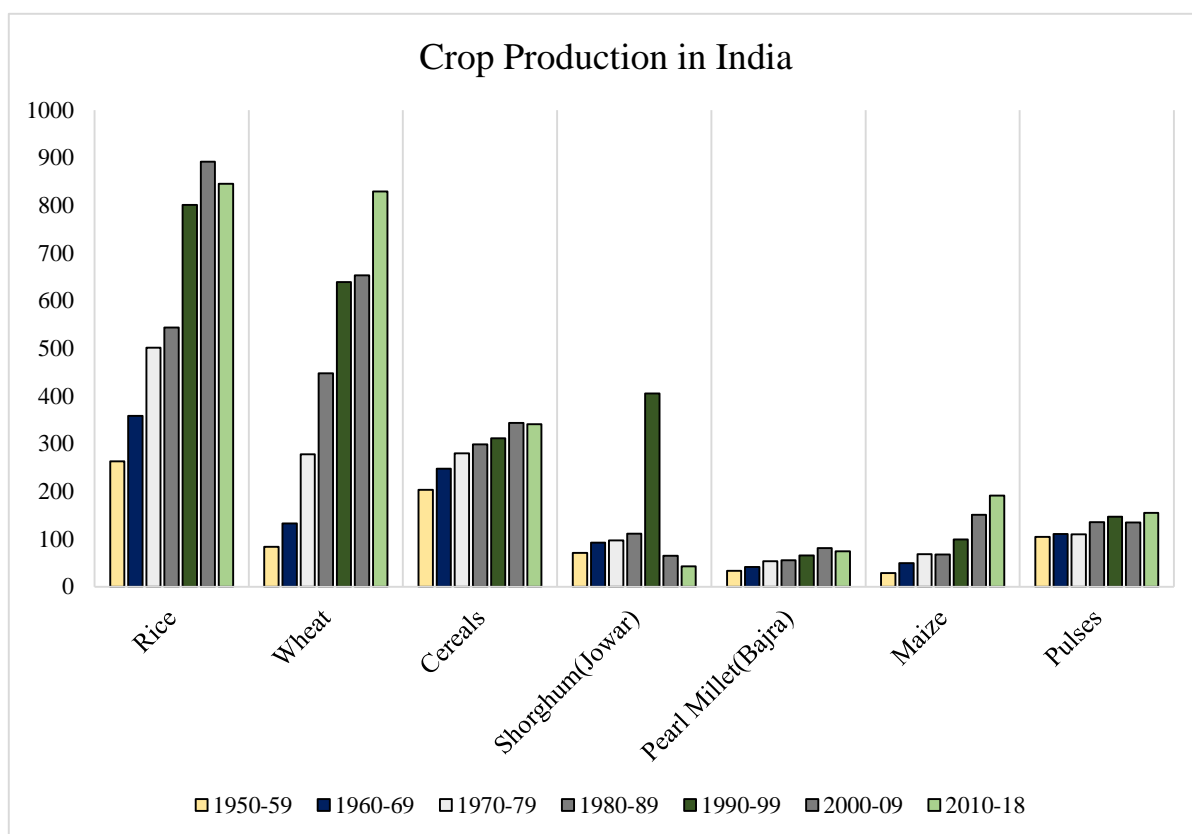


Fig. 3.1: Trend in Food Crop Production in India 1950 to 2018

Source: (Agricultural Statistics at a Glance 2018, 2019)

The adoption of Green Revolution has led to the change in land use pattern (Table 3.1) in Rajasthan as well. Factors such as use of pesticides and fertilizers, per capita food production index, cultivated area and area under forests impact the spatial land distribution. From 1960's to 2001 there is variations in the arable land. As a result of varying land under cultivation, crop productivity too shows a fluctuating pattern (Fig. 3.2).

In the following sections the cropping scenario in Rajasthan has been discussed followed by formulation of mathematical model. The model formulated discuss crop-mix, crop-combinations and the cropping pattern adopted by growers in a region. Further, the impact of climate on crop yield when cultivated as a mix-crop and how the crop-combination impacted the crop yield were evaluated. To develop a model certain assumption were made.

Table 3.1: Land-Use Pattern in Rajasthan

Year	1960-61		1970-71		1980-81		1990-91		1999-2000		2000-2001	
	Area	Productivity (% share)	Area	Productivity (% share)	Area	Productivity (% share)	Area	Productivity (% share)	Area	Productivity (% share)	Area	Productivity (% share)
Geographical Area	33841	100	34109	100	34227	100	34252	100	34258	100	34265	100
Forest	814	2.4	1355	3.97	2088	6.10	2353	6.86	2580	7.53	2606	7.61
Land under non-agriculture use	1095	3.23	1162	3.40	1507	4.40	1490	4.35	1725	5.04	1740	5.08
Uncultivated/barren	5153	15.22	4716	13.82	2917	8.52	2790	8.14	2580	7.53	2566	7.49
Area not available for cultivation	6248	18.46	5878	17.23	4424	12.92	4280	12.49	4305	12.57	4306	12.57
Permanent Pastures	1684	4.97	1807	5.29	1834	5.35	1912	5.59	1714	5.00	1707	4.98
Miscellaneous land	16	0.04	9	0.02	24	0.07	22	0.06	14	0.04	14	0.04
Cultivable wasteland	6841	20.21	6112	17.91	6415	18.74	5567	16.25	4988	14.56	4908	14.32
Uncultivated land excluding fallow land	8541	25.23	7928	23.24	8273	24.17	7501	21.89	6716	19.60	6629	19.34
Other than fallow land	3104	9.17	9326	27.34	2089	6.10	1927	5.62	2511	7.33	2444	7.13
Current fallow land	2022	5.97	1443	4.23	2085	6.09	1814	5.29	2637	7.70	2415	7.05
Total fallow land	5126	15.14	3769	11.04	4174	12.19	3741	10.92	5148	15.03	4859	14.18
Net sown area	13112	38.74	15179	44.50	15268	44.60	16377	47.81	15509	45.27	15865	46.30
Total cropped area	14013	41.40	16720	49.01	17350	50.69	19380	56.58	19286	56.30	19230	56.12
Area sown more than once	901	2.66	1550	4.54	2082	6.08	3003	8.76(15.49)	3777	11.02(19.58)	3365	9.82(17.49)

Source: (Planning Commission, Government of India, 2006)

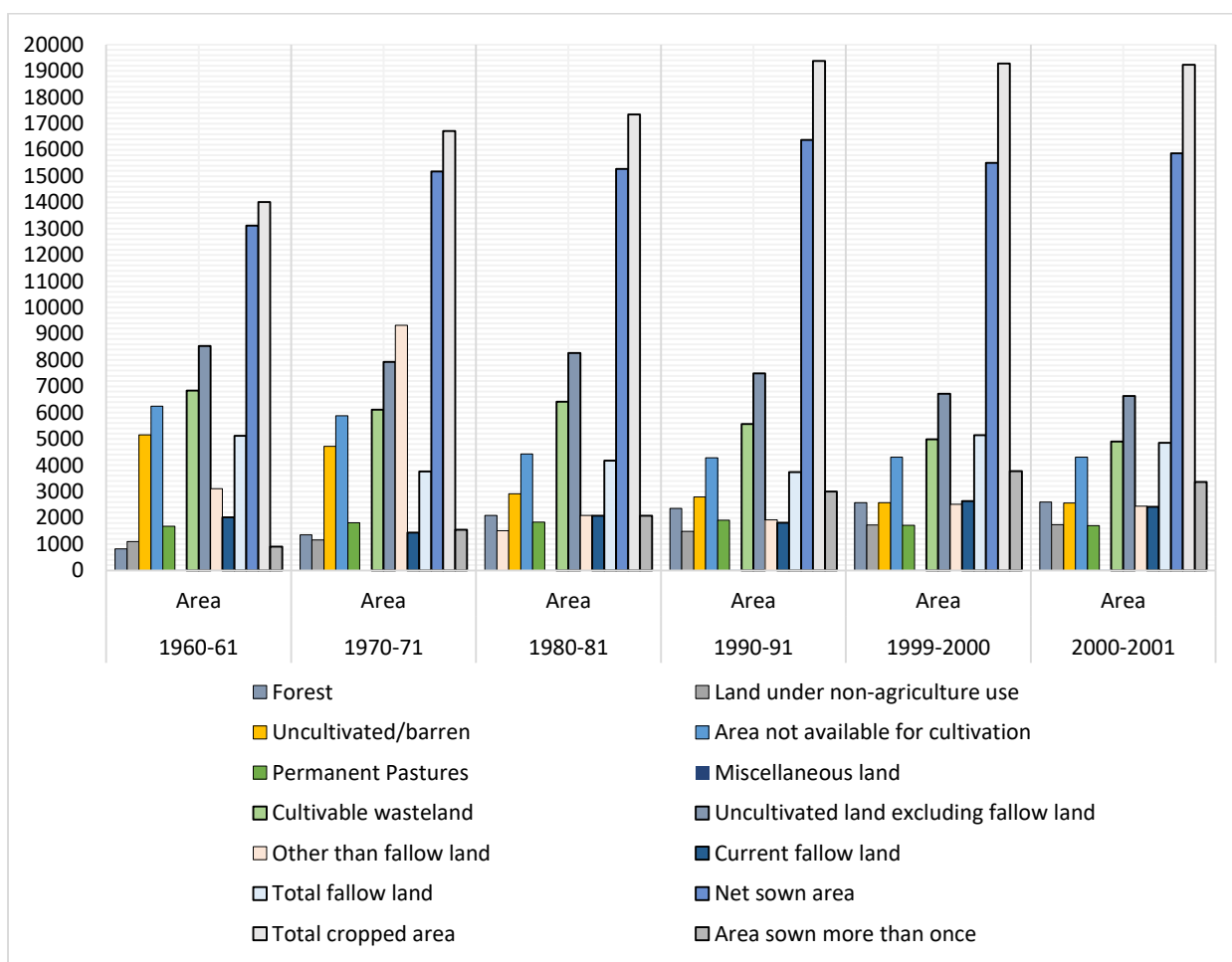


Fig. 3.2: Land-Use Pattern in Rajasthan (1960-2001)

3.3 Cropping Trends in Rajasthan

Topographical conditions and geographical location of the state supports the diversified variety of cultivation. Rajasthan experience two major cropping seasons namely Rabi and Kharif. Kharif crops account 14.1% (Government of Rajasthan & Department of Agriculture, 2020a) of the state’s arable land. Some of the commonly cultivated crops in a season include green gram, beans, moth, maize, sorghum, sesame, pearl millet and urd. Rabi crops accounts 106.18% (Government of Rajasthan & Department of Agriculture, 2020b) of the total cropped area. Wheat, mustard, black gram and barley are some of the majorly cultivated crops in a season (B. L. Sharma, 2000). The reason for low percentage of cultivated region in Kharif season is the inadequate availability of water resources.

Besides these crops, state supports the cultivation of diverse variety of oilseeds, vegetables and fruits. The farmers in a region practice mix-cropping, multiple-cropping and mono-crop

pattern. Rajasthan is the largest producer of pearl millet in India. Between these two seasons there is a short duration season known as Zaid that supports the cultivation of groundnuts.

3.3.1 Cropping Pattern in Rajasthan

Allocation of crop, crop combination, operational activities involved for better productivity are some of the most significant decision variables that needs to optimized in every growing season. Rajasthan being arid and semi-arid often face water inadequacy situations. Majority of cultivation in a region is rain-fed. However, water inadequacy emerges as one of the major factors affecting the agriculture sector. Thus, there is a need to allocate the water resources efficiently. For optimizing water resources different cropping pattern were adopted by growers. For allocation of irrigation resources under water deficient conditions, an optimal model is developed by (Shangguan et al., 2002). Model results indicate that the allocation of crops and water resources for irrigation depends on the economic benefit per unit area cultivated under each crop. Consequently, these benefits or profits depends on market conditions and operational cost. Thus, it is necessary to consider the cropping pattern and allocation of resources according to availability and market demand. Consequently, to overcome the issue of crop allocation, researchers contribute to determine the feasibility of solution by developing a mathematical model.

Mathematical output or representation of farm constraints, enables the policymakers to determine the areas in which the changes will be carried out to reduce the loss and increase the profits. Thus, different mathematical techniques is used by (Aparnathi, 2014) for crop allocation depending on available resources. Regional agricultural model proposed, is based on the data collected from different districts of Rajasthan. Model will provide an ‘optimal’ land-use and crop combination allocation plan. Multi-Objective Linear Programming approach is used to get an optimized results for crop production subject to the set of constraints. (Chen & Önal, 2012) explains that the optimized solution of the Linear Programming model is formed by compiling or stacking all the extreme points. Thus, the optimized farm model reflects the optimum responses of all the parameters that the decision-makers take to allocate their resources in an optimized model framework.

From literature reviewed, crop allocation is considered one of the major factors to determine farm revenues. These decision parameters were further investigated by (Dury et al., 2012b) to determine the effect of short and long-term decisions on crop productivity. Hence, to support the farmers, decision support model was developed to allocate the resources efficiently. Studies

had been carried out to determine the feasibility of decision variables by using different mathematical and statistical tools. Further, by interviewing the farmer, it is observed that there are many crops that provide more economic benefits, but due to financial constraint and inadequate water resources in a region, growers are not able to cultivate these crops.

To determine the effect of crop rotation on farm revenues a mathematical model is formulated by Castellazzi et al. (2008) . A systematic and concise mathematical representation of crop rotations were proposed. The mathematical model formulated by the researchers makes it easier for the policymakers and particularly for the growers to allocate the available resources efficiently to get an optimized farm output.

Small farmers (owning small piece of land) in Rajasthan often practice a mix-crop pattern with the aim to utilize the available resources optimally. By interviewing the farmers in a region, it is analyzed that such a farm scenario provides a model of integrated farm scenario. Filippi et al. (2017) proposed a mathematical model to optimize a land resources for opted crop-mix. The complexity of a sector is due to several varying decision variable such as pest attack, climatic variations, soil moisture content and so on. As a result of scarce availability and uneven distribution of resources, concept of mixed-cropping pattern is proved beneficial in some regions of Rajasthan. Such arrangement of crops optimizes land and other resources to their full extent and provides better outputs. Mixed cropping results in more crop yield, stability of production, reduces the pest attack, improves soil content and reduces the risk of crop failure. Thus, to evaluate the benefits of mixed cropping system, Jolayemi & Olaomi, (1995) develop a mathematical formulation for an efficient integration and management of all the farm components.

In mix cropping pattern one of the most crucial decisions is to consider the crops that would compete with each other in terms of resources. During the survey, it is observed that the farmers generally support their mixed cropping with a livestock. This results in an integrated farm scenario. The farm considered to formulate a mathematical model is cultivated with grams, wheat, lemon, chilies, gourd, aukra, tomatoes and coriander. Along with crop allocation farmer allocates some part of his farm for livestock (goat, cows, buffaloes and poultry) too. Due to livestock keeping his cost of fertilization and manuring almost slashed to $\frac{3}{4}$ th of the cost that he invested earlier in fertilization. Moreover, because of natural fertilizer input farm output rose to about 2% of what he practiced earlier. Based on integrated farm system, a mathematical model is formulated. The model developed with the aim to determine optimal crop

combinations that will increase farm productivity. In mixed cropping pattern it is not possible to allocate a defined area to each crop that is considered for cultivation. Large farmers generally, did not adopt this cropping pattern as they have sufficient land and other resources to allocate the crops. Thus, a mathematical model developed for mixed cropping pattern.

Model Assumptions

1. Topographical features of a region were assumed to be constant.
2. The effect of soil parameters such as pH, bulk density, electrical conductivity is not taken under consideration for mathematical formulation.
3. To support the farm activities, farmers have a livestock the cost coefficient of livestock is not included in optimality function.

3.3.2 Crop-Mix Model

Notations

$l \in L$: location available for planting

$j \in J$: Potential crops cultivated/ variety cultivated

$p \in TP$: set of feasible crops (j^{th} crop) cultivated in p period in i^{th} season

r_{ij} : expected revenue per hectare from j^{th} crop in i^{th} season (in Rs.)

e_{ij} : effect of j^{th} crop when planted as a mixed crop in i^{th} season

s_{ij} : the seeds procured for j^{th} crop in i^{th} season (Rs./kg)

x_{ij} : planted area per hectare under j^{th} crop in i^{th} season

P : the amount for the procurement of seedlings (Rs.)

p_{ij} : amount of fertilizers and pesticides required in the growth of j^{th} crop in i^{th} season (Rs./ha)

CP_{ij} : cost of planting (in Rs.) j^{th} crop in i^{th} season per hectare

CC_i : cost of cultivation in i^{th} season per hectare (Rs./ha)

C_i : total capital available in i^{th} season (Rs.)

HC_{ij} : harvesting cost of j^{th} crop per hectare in i^{th} season (Rs.)

H : capital allotted for harvesting (Rs.)

LA : total available land for cultivation (ha)

TCA_{ij} : total capital available for cultivation of jth crop in ith season

CR_{ij} : cultivated area under jth crop in ith season

TOC_i : total farm operating cost in ith season

WR_i : water required in ith season for irrigation

TWA_i : total quantity (liters) of water available for irrigation in ith season

L_{il} : cost of seasonal labour required in ith season at location l

HL_{il} : cost of workers hired in ith season at location l

Plant_{ijkl} : area planted under crops in ith season at location l (in hectares)

Min_{jk} : minimum area planted under crop (jth and kth)

Max_{jk} : maximum area planted under crop (jth and kth)

Objective Functions

$$\text{Max. } X = \sum_{i=1}^n \sum_{j=1}^m r_{ij} X_{ij} + \sum_{i=1}^n \sum_{j=1}^m \sum_{k=1}^{m-1} e_{kj} X_{ki} r_{ki} \quad (\text{Total Farm Revenues})$$

$$\text{Min. } Y = \sum_{i=1}^n (\text{THC}_i + \text{CC}_i + \text{TOC}_i) \quad (\text{Total Farm Cost})$$

$$\text{Min. } Z = \sum_{i=1}^n \text{WR}_i \quad (\text{Water Requirement})$$

$$e_{ij} = \begin{cases} 0, & \text{if } j^{\text{th}} \text{ crop has no effect on the crops with which it is cultivated in } i^{\text{th}} \text{ season} \\ \text{positive,} & \text{if crop production (} j^{\text{th}} \text{ crop) indicates a growth in } i^{\text{th}} \text{ season} \\ \text{negative,} & \text{if crop production (} j^{\text{th}} \text{ crop) indicates a reduction in } i^{\text{th}} \text{ season} \end{cases} \quad (3.1)$$

Constraints

$$\sum_{i=1}^n \sum_{j=1}^m s_{ij} x_{ij} \leq P \quad (3.2)$$

$$\sum_{i=1}^n \sum_{j=1}^m p_{ij} x_{ij} \geq 0 \quad (3.3)$$

$$\sum_{i=1}^n \sum_{j=1}^m CP_{ij} x_{ij} \leq \sum_{i=1}^n CC_i \quad (3.4)$$

$$\sum_{i=1}^n \sum_{j=1}^m HC_{ij} x_{ij} \leq H \quad (3.5)$$

$$\sum_{i=1}^n \sum_{j=1}^m CR_{ij} \leq LA \quad (3.6)$$

$$P+H+\sum_{i=1}^n CC_i + \sum_{i=1}^n TOC_i \leq \sum_{i=1}^n \sum_{j=1}^m TCA_{ij} \quad (3.7)$$

$$\sum_{i=1}^n WR_i \leq \sum_{i=1}^n TWA_i \quad (3.8)$$

$$\text{Min}_{jk} x_{jki} \leq \text{Plant}_{ijkl} \leq \text{Max}_{jk} x_{jki} \quad (3.9)$$

$$HL_{il} \geq L_{il} \quad (3.10)$$

The mathematical model formulated is limited with set of constraints defined in terms of mathematical equations as presented above. Equation (3.2) represents the costs of procuring seeds for j^{th} crop in i^{th} season, (3.3) illustrates the cost of procuring fertilizers and pesticides required for the growth of j^{th} crop in i^{th} season, (3.4) illustrates the cost of planting a crop j in i^{th} season, (3.5) illustrates the cost of harvesting the j^{th} crop in i^{th} season.

Equation (3.6) represents the cultivated area under j^{th} crop in i^{th} season followed by total (3.7) operating cost of the field for the cultivation. Equation (3.8) illustrates the water required for the cultivation in i^{th} season, equation (3.9) illustrates that the area cultivated under each crop must restricted within minimum and maximum area available for cultivation and (3.10) illustrates the cost of labor (needed during harvested and sowing season).

Best possible way to get an optimal crop-mix combination for a mixed cropping pattern is to select the crops of same group.

The estimated cost of farm practices per hectare with respect to each crop and the interaction effect per hectare of cultivating the crop simultaneously with each other is illustrated by Table 3.2.

Table 3.2: Cost of Cultivation of each Crop per Hectare (000'Rs.)

Crop j	Cost (in Rs.)							
	x1	x2	x3	x4	x5	x6	x7	x8
x1	8	9	7	6	4	8	9	8
x2	4	3	6	5	2	1	4	4
x3	4	3	3	2	5	6	1	5
x4	8	4	8	9	6	5	6	4
x5	3	2	4	1	7	8	4	4
x6	9	2	4	5	8	7	8	3
x7	8	6	5	7	2	4	5	7
x8	7	6	5	7	2	4	5	2

Table 3.3: Optimal value of the decision variable

Decision Variable	x1	x2	x3	x4	x5	x6	x7	x8
Optimal Value	10.0	15.0	15.0	30.0	36.0	4.0	10.0	35.0
Optimized value of Objective Function (Rs.)	10,295							

The model results show that all the crops cultivated contribute in feasible optimal solution. The optimal value of the decision variable is illustrated in table 3.3. The solution optimality indicates that all decision variables satisfy the set of constraints and non-negativity conditions.

Multi-objective linear programming approach is being used to determine the feasibility of decision variables. In real scenario decision makers often confronted with several objectives

having a mutual conflict. These objectives not always agreed to be either minimized or maximized simultaneously. For instance, small farmer with a limited arable land available for cultivation focusses to minimize the operating cost including: cultivation cost, harvesting cost, labour cost, minimize the use of scarce resources with the aim to maximize the production and hence the revenue. However, in such a scenario the application of Linear Programming approach will provide a solution optimality either by minimization of operating cost or maximization of production.

Furthermore, in traditional optimization techniques there is a need to find a proper balance between the optimality of objective function and minimization of requirement vector. Hence, we find that MOLP is more appropriate in determining the feasibility as the approach enables the decision makers to operate with the vague concept of the relative importance of the objective function. Moreover, in linear programming optimization, the optimal solution is unique as the approach focus to get feasible decision variable space on other hand, MOLP extends the optimization process by allowing the single objective to be optimized simultaneously rather than focussing on only minimization and maximization of objective function.

3.3.3 Crop-Combination Model

The set of crops chosen for cultivation in a particular season is an issue of concern for growers. However, these decisions are often influenced by other farm parameters too. Thus, to investigate the constraints that limits or influence the farmers decision, a case study is being discussed. The study is carried out in Jaipur district of Rajasthan. A farm cultivated with multiple crops throughout the season is being modelled. The model discussed is employed to determine the optimal crop pattern. One of the constraints that need to be imposed is the land under each crop. Four different crops cultivated in Rabi and Kharif season are considered. Different sets of the crops were modelled and analyzed to determine the best possible crop combination were illustrated in table 3.4 (in Rabi season) and table 3.5 (in Kharif season) respectively.

3.3.4 Model Formulation

We aim to maximize the farm's profit on the basis of the decision made by the farmer. Thus, the choice of crop combinations in both Rabi and Kharif season is being evaluated. The crop choice depends on how profitable that choice is likely to be.

We assume that the farmers profit in choosing a crop j ; $j=1,2,3,\dots,m$ in i^{th} season is

$$\pi_{ij}=V(K_j,S_j)+\varepsilon(K_j,S_j) \quad (3.11)$$

Where, K represents exogenous farm variables that includes, soil, climate, water and other variables and S is a vector of characteristics of farm that include farm size and other fixed variables. The function is composed of two components one is the error term and other is the observed output V i.e., crop yield production. The farmer will choose the combination that yields maximum profit.

Defining $Z=(K_{ij},S_{ij})$, farmer will choose the crop k over the j if;

$$\pi^*(Z_{ki})>\pi^*(Z_{ji})\forall k \neq j \quad (3.12)$$

The probability P_{ji} of being chosen in the combination is

$$P_{ji}=\Pr(\varepsilon(Z_{ki})-\varepsilon(Z_{ji})<V_j-V_k)\forall k \neq j \text{ where } V_j=V(Z_{ji}) \quad (3.13)$$

In addition, to get an optimized crop combination we measure the climate sensitivity of the crop choice by estimating the relationship between crop choices and farm variables. The agronomy literature indicates a non-linear relationship between climate parameters and crop growth. According to (Greene, 2003), the change in expected probability for the infinitesimal change in climate variable will estimate the climate sensitivity. The model is then used to predict the marginal impact of climate change on crop yield.

Table 3.4: Optimal Solution of the MOLP Problem (Rabi Season Crops)

Crop Combinations	Optimal Value of Decision Variable	Optimal Value of objective function (in Rs.)
1,2,3,4	$x_1^*=5, x_2^*=20, x_3^*=60, x_4^*=60$	65,475*
1,2,3	$x_1^*=25, x_2^*=30, x_3^*=45$	43,425*
1,2,4	$x_1^*=20, x_2^*=20, x_4^*=25$	29,975
1,3,4	$x_1^*=5, x_3^*=45, x_4^*=5$	23,550
2,3,4	$x_2^*=20, x_3^*=60, x_4^*=60$	63,800*
1,2	$x_1^*=25, x_2^*=40$	28,575

1,3	$x_1^* = 5, x_3^* = 25$	12,550
1,4	$x_1^* = 25, x_4^* = 30$	28,950
2,3	$x_2^* = 20, x_3^* = 40$	27,500*
2,4	$x_2^* = 20, x_4^* = 35$	26,200*
3,4	$x_3^* = 25, x_4^* = 300$	24,675

Note*: x_i^* denotes the optimal value of the decision variables

The mathematical models discussed above is formulated from a real data set obtain by interviewing the farmer. LINGO 18.0 (LINGO 18.0 has inbuilt LP Solver thus no coding is done) and SOLVER software is used to find a model solution. The farmer owning 65 hectares of land, practicing multiple crops is being discussed to analyze the model results. Out of total arable land 60 hectares of land is cultivated. The farm is cultivated in both Rabi and Kharif season. In Rabi season farm is cultivated with mustard, wheat, black gram and barley. In Kharif season it is cultivated with sorghum, maize, pearl millet and green gram. The decision of crops to be cultivated depends on the water availability and other available farm resources that were represented as a set of constraints. The impact of climate parameters on the crop yield is illustrated with the help of contour plots (Fig. 3.3) below. The graph indicates the yield variability with respect to change in climate parameters.

Table 3.5: Optimal Solution of the MOLP Problem (Kharif Season Crops)

Crop Combinations	Optimal Value of Decision Variable	Optimal Value of objective function (in Rs.)
1,2,3,4	$x_1^* = 25, x_2^* = 9, x_3^* = 15, x_4^* = 10$	10,035
1,2,3	$x_1^* = 10, x_2^* = 20, x_3^* = 15$	7,350
1,2,4	$x_1^* = 16, x_2^* = 30, x_4^* = 8$	15,600*
1,3,4	$x_1^* = 8, x_3^* = 30, x_4^* = 12$	14,060
2,3,4	$x_2^* = 25, x_3^* = 12, x_4^* = 10$	12,480
1,2	$x_1^* = 17, x_2^* = 36$	10,835
1,3	$x_1^* = 16, x_3^* = 27$	6,400

1,4	$x_1^*=45, x_4^*=8$	5,665
3,4	$x_3^*=35, x_4^*=21$	18,585*
2,3	$x_2^*=25, x_3^*=39$	14,110
2,4	$x_2^*=45, x_4^*=16$	16,310*

Note: x_i^* denotes the optimal value of the decision variables*

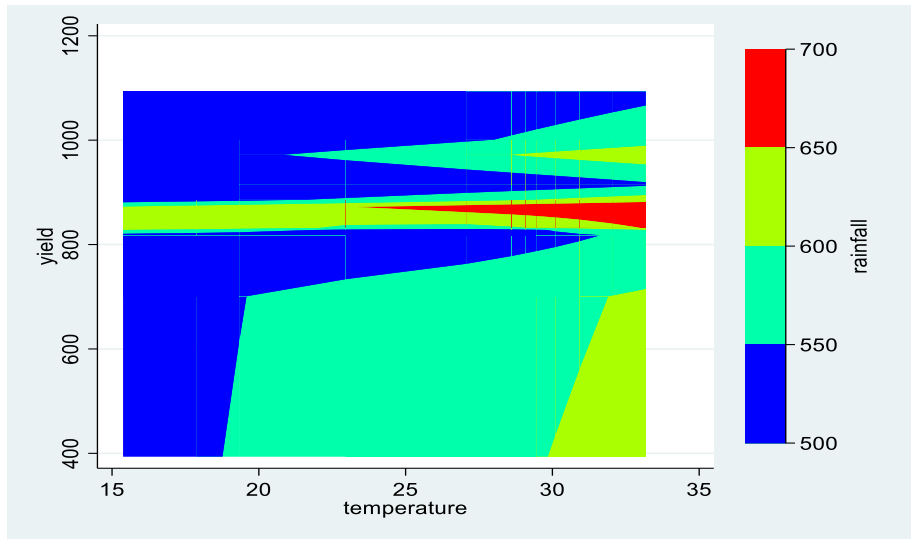


Fig. 3.3.1: Crop Variability (Pearl millet)

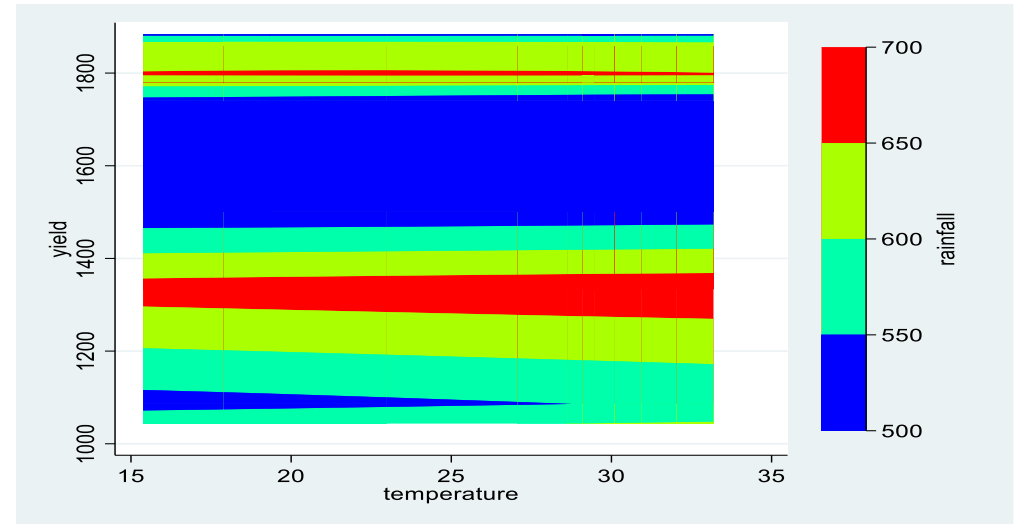


Fig. 3.3.2: Crop Variability (Maize)

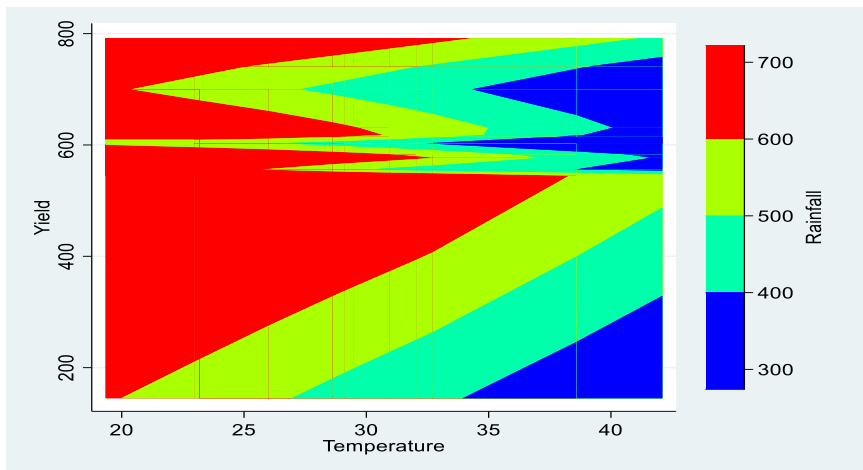


Fig. 3.3.3: Crop Variability (Sorghum)

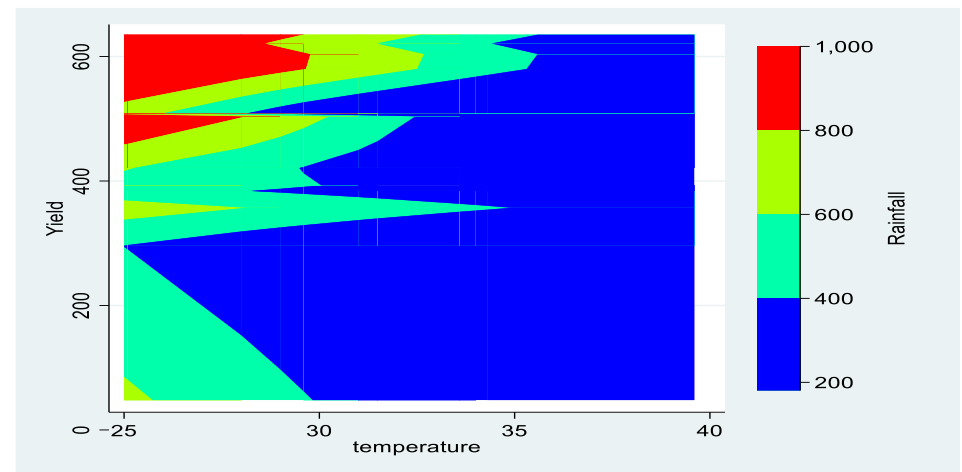


Fig. 3.3.4: Crop Variability (Green gram)

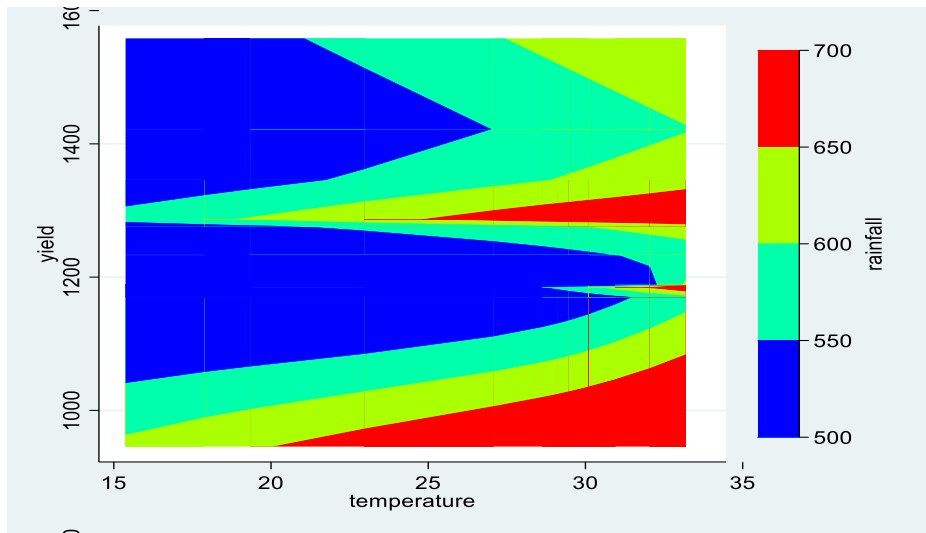


Fig. 3.3.5: Crop Variability (Mustard)

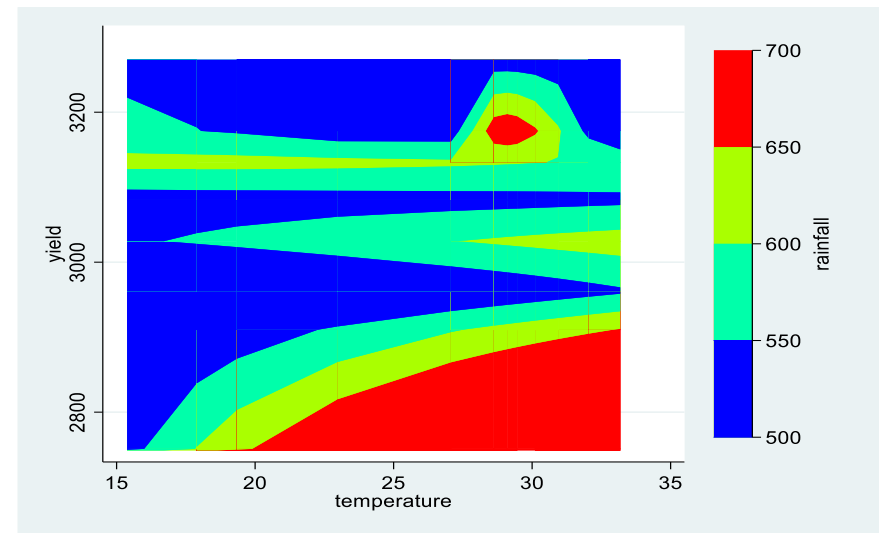


Fig. 3.3.6: Crop Variability (Wheat)

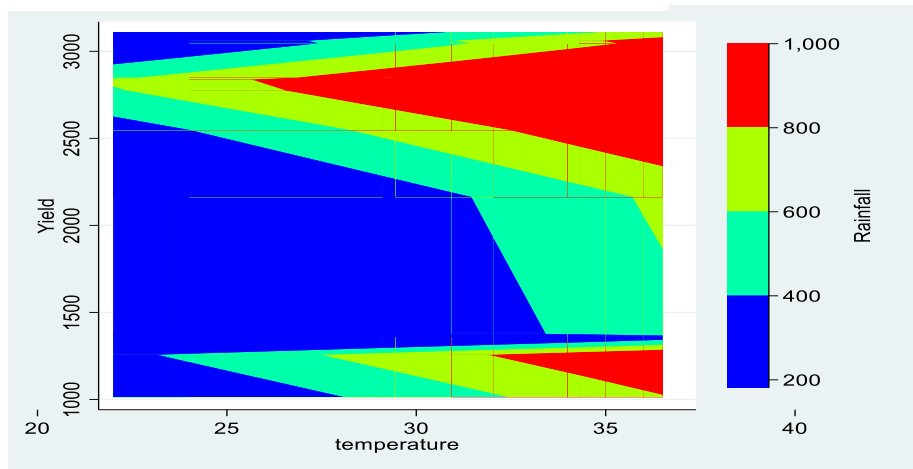


Fig. 3.3.7: Crop Variability (Barley)

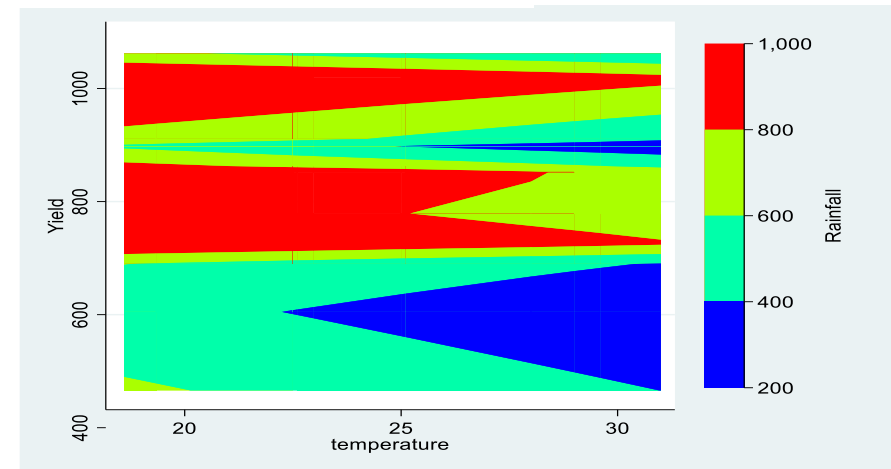


Fig. 3.3.8: Crop Variability (Black Gram)

Fig. 3.3: Crop Yield Variability-Respond to Climate Change

Plots (Fig. 3.3) indicate the yield variability in response to temperature and rainfall for the set of crops considered for cultivation. During data collection from different districts of Rajasthan one of the major challenges that the growers have to face is the scarcity of the available water resources for irrigating their fields. Thus, for a model formulation available irrigational water is formulated as one of the constraints. Consequently, irrigation scheduling has become another challenge for the researchers to look into (Pereira et al., 2013). As the crop-water response at different stages is non-uniform, it became crucial for the decision-makers to choose an optimized path to allocate the deficits among the crop.

The issue of water allocation became more complex when it has to allocate among multiple crops. Thus, the crop combination discussed above is so chosen such that the crops can compete with each other in terms of available irrigational water. The wheat requires more water as compare to other cultivated crops. In addition, to improve the production, farmers often practice crop rotation. This practice improves the crop yield and production. However, (Hazell, 1984a) argues that the uniform farm practices are one of the major causes of yield reduction. Thus, different cultivation practices such as crop rotation must be practiced to improve the crop yield and allow the soil to retain its nutrients.

All the variable under investigation follows a non-negativity condition. Further, the model can be modified by using sensitivity analysis. An analysis provides with the range up to which the activity coefficient and requirement vector can vary within a feasible region. From the result (Table 3.4 & 3.5), it can be concluded that the crops chosen for cultivation is an optimal crop combination for the farm under study, based on the resources available. The feasibility in the acreage under each crop is determined and it is found that the crop set (1,2,3,4) provides a best optimal output in Rabi season and (3,4) in Kharif season respectively. The variations suggested in crop cultivation sequence enables to choose an optimal crop combination. However, in practice farmer cultivate a crop set (2,4) in kharif season which is a combination of maize and sorghum and a crop set (1,2,3) which is a combination of wheat, mustard and black gram. The model result suggests that if the crop set (1,2,3,4) in Rabi season and (3,4) in kharif season is adopted by farmer then he would able to generate more farm revenue as compared to the crop set that he is practicing. Changes made in requirement vector and particularly in area under each crop altered the results.

The data collected from Banswara district of Rajasthan shows that the growers in a region prefer mono-cropping irrespective of farm size. The reason behind this is that the district faces

inadequate availability of water resources thus, majority of the crop in a region is rain-fed. Majorly cultivated crop in a region include sesame and maize. Generally, most of the farmers owning large farms adopt multiple-cropping rather than a mono-crop system.

However, (Morrison et al., 1986) argued that it is quite difficult to compare the solution of mathematical programming model with reality as there are many minor constraints that the farmers have to face in each growing season that may be overlooked while formulating a model. Thus, the formulated mathematical model will provide an approximate result. The decision-making process to determine the optimal crop combination is as follows (Fig. 3.4)

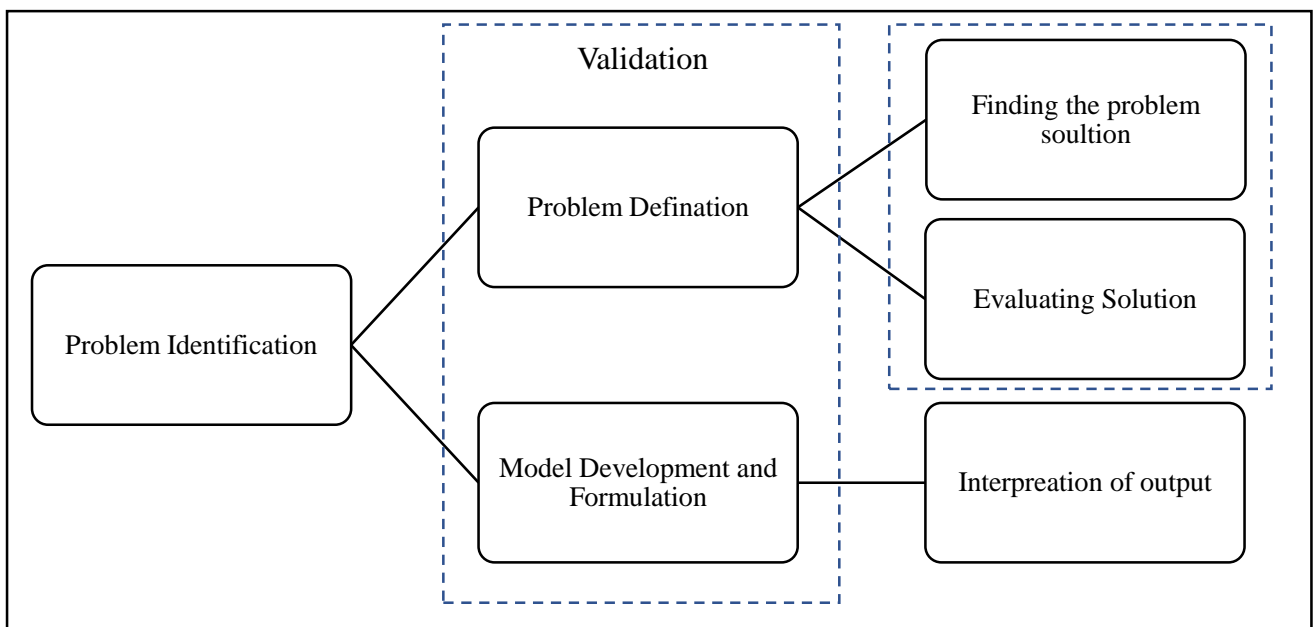


Fig. 3.4: Decision-Making Process

Traditionally, the crop allocation is based on farmers experience, instincts and thumb rule forecasting. However, in present scenario the development of capital intensive production system and the use of quantitative planning methods is based on development and analysis of a mathematical model (Filippi et al., 2017b). So, far none of the model of this kind is formulated for the Rajasthan agriculture scenario. Thus, the study is an effort to contribute to extend the literature in the direction for optimal allocation of crop with mathematical approach.

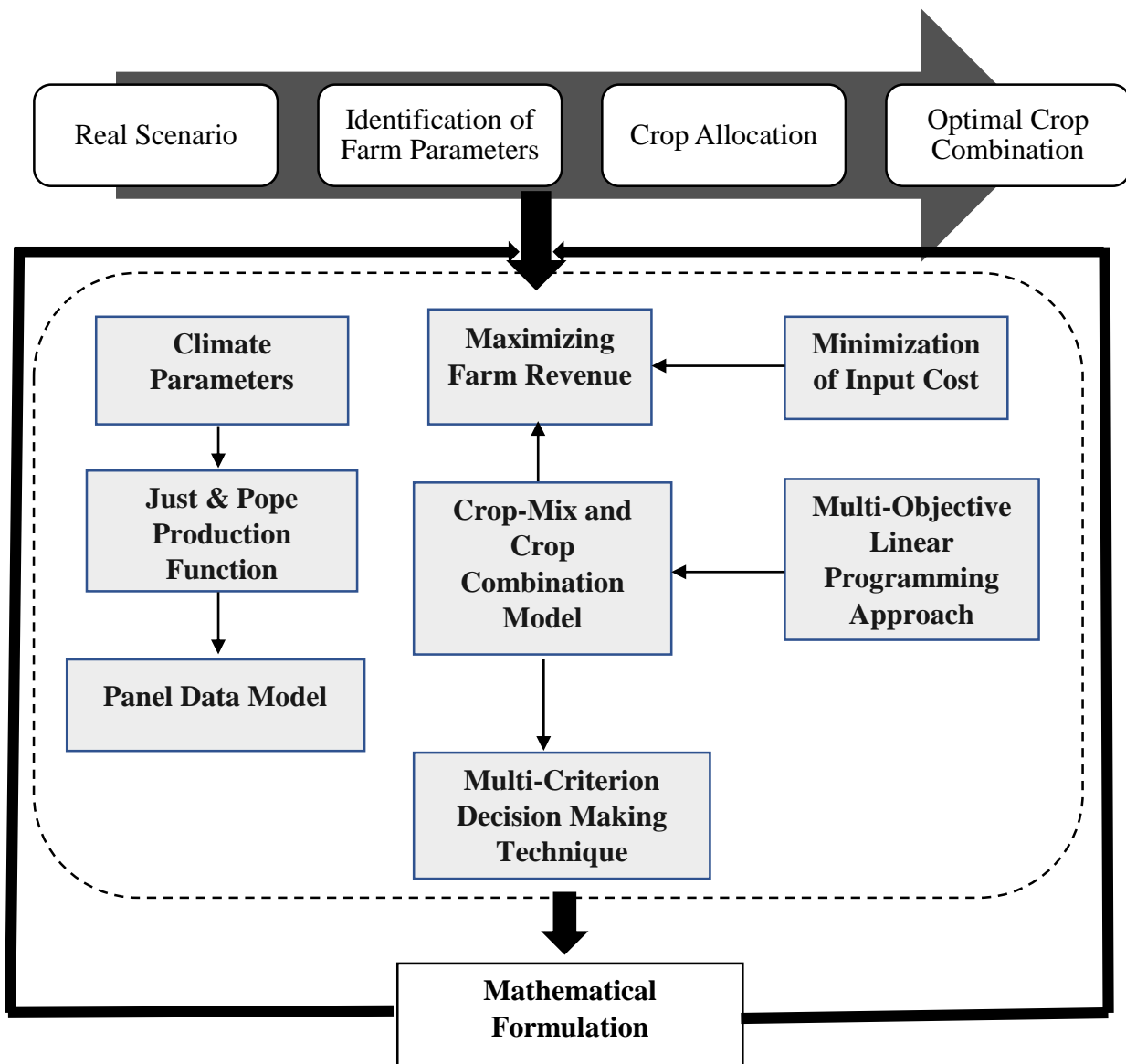


Fig. 3.5: Systematic Framework for Optimal Crop Selection

The model discussed is further modified by including climatic parameters. It is found that the climate parameters; rainfall and temperature has positively influenced the mean crop yield and its variability for some crops and vice-versa for others. The average values of climate parameters are considered for study as it is difficult to determine the impact of these variations on crop yield.

However, different statistical approaches have been used by the researchers to determine the impact of climate on mean crop yield (Isik & Devadoss, 2006; Shirley et al., 2020). It is realized that the crop combination model discussed above provides a deterministic approach to evaluate

the impact of fixed variable on crop allocation and combinations. But the crop choice and its distribution vary with climate as well.

Understanding the relationship between crop yield and climate helps in enhancing the resilience of agricultural production systems to climate change (Leng & Huang, 2017). Crop allocation and climatic changes have comprehensive impact on crop productivity. Only few studies (Qiao et al., 2018) have been conducted that evaluate the impact of crop distribution and climate change on crop production.

One of the issue with the formulation of climate model is the correlation between different climate parameters which makes it difficult to interpret exactly how much of the observed correlation between yields and average temperature is due to actual scenario and how much is due to a very hot days or reduced precipitation that supposed to be correlated with average temperatures (D. Lobell, 2010). Thus, collinearity among the variable makes it difficult to evaluate yield change in respond to single climate variable. The best approach to deal with this is to choose a sample where the sample variables are not highly correlated. Fig. 3.5 indicates the impact of climate variables on crop yield. The graph plotted between yield and climate parameters indicates that the data points are randomly distributed over space indicating that there is low correlation between these attributes. Since there are numerous other parameters impacting the yield thus the graph illustrates the randomness in data points.

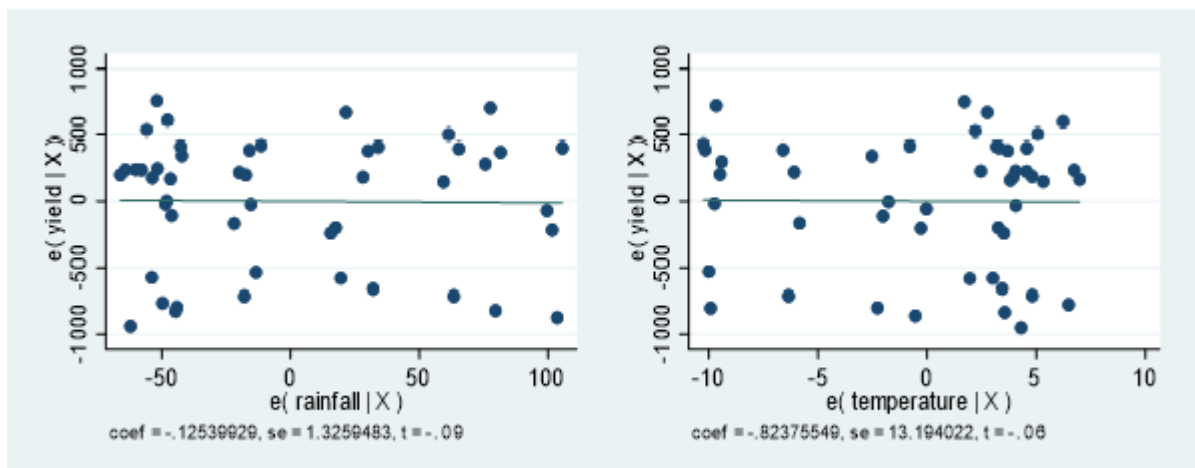


Fig. 3.5: Scatterplot of the Yield Versus the Climate Parameters

To predict the impact of one factor over the other it is important to opt the correct functional form (Isik & Devadoss, 2006) that is capable to describe the relationship between predictor variable X and yield response variable Y. The best way to choose the appropriate functional form is to examine a scatter plot of a data as shown in Fig. 3.5. In addition, the squared term

of variables is very important, as it significantly improves the model. Next chapter will discuss the impact of rainfall and temperature on mean crop yield and its variance in detail with the help of Just & Pope production function.

Crop choice adaptation to a climate change is frequently investigated by researchers, mathematician and statisticians. Farmers make crop choice on the basis of available cultivable land, labour, government policy, environmental conditions, soil composition, and available surface flow. However, studies had been carried out to determine the impact of these parameters (B. Abdelaziz, 1978; Ahumada & Villalobos, 2011c; Aparnathi, n.d.; C. Yang et al., 1998c; Krummel & Su, 1996; Qiao et al., 2018; Semenov & Porter, 1995; Warrick & Gardner, 1983; Wineman & Crawford, 2017b) on crop yield and hence on farm revenue. Thus, analysis is being carried out to select an optimal crop with respect to climatic variations.

Now the question arises, how important are these different crop factors to crop choice? What is the role of climate in crop choice? As the climate changes how it will affect the crop choice? Thus, in the following section we will discuss the climate sensitivity of specific crop choices made by the farmers in Rajasthan for a mix-crop practice. To overcome the extreme climatic fluctuations there is a need to develop an adaptation strategy. However, in literature available (Dharmaraja et al., 2020) there exist only few mathematical modulations of how farmer will adopt a variation in climate. By examining the crop choices that farmers made across different agro-climatic zones, provides a better understanding how different climatic zones have adapted the climate change.

3.3.5 Crop-Choice Model: Climate Sensitivity

In a changing climatic condition understanding the influence of climate parameters on crop yield is necessary for enhancing agriculture resilience. In general, extreme climatic conditions results in reduction in crop yield. Estimating the impact of climatic fluctuations on crop yield, researchers (S. Asseng et al., 2013; Challinor et al., 2014; E. Wang et al., 2017; Wheeler & von Braun, 2013) tries to quantify yield respond to climatic variations.

To evaluate the impact of climate on crop yield two climate variables namely, rainfall and temperature is being analyzed by applying multiple regression analysis. Rainfall and temperature are selected to represent first-order climatic impacts on yield, while the change in yield is estimated by area allocated under each crop. The reason behind choosing the area as one of the parameters is to estimate how the crop productivity will get affected when multiple

crops were cultivated simultaneously as a result of climatic variations. Extreme climatic variations are not considered for evaluation. Temperature (T), rainfall (R) and area (A) were considered as predictant and crop yield as dependent variable.

$$Y_{j,i} = \beta_0 + \beta_1 T_{i,j} + \beta_2 R_{i,j} + A_{i,j} + \varepsilon_{i,j} \quad (3.14)$$

where, β 's represent the coefficient for j^{th} crop in i^{th} season, $\varepsilon_{i,j}$ are the model residuals illustrated in graphs below. Since each crop has different agro-climatic requirement for producing optimal yield; thus, in-depth analysis of climatic variability supports to enhance the productivity.

The parameters were detrended before they were used for fitting the models. The coefficient of determinant is calculated to determine the variability in crop production. Regression model which empirically fit the linear climate-yield relation indicates that significant variability is induced by climatic variation.

Table 3.6: Multiple Crop Choice Regression Model (Kharif Season)

Pearl millet		Pearl millet		Pearl millet	
Maize	0.3416	Sorghum	-0.0003	Green gram	0.0000
T	3.9029	T	-10.6545	T	-20.6398
R	0.6059	R	-0.2621	R	-0.1225
A	0.9867	A	0.7851	A	0.7521
Coefficient of Determination	0.7516	Coefficient of Determination	0.9218	Coefficient of Determination	0.7724
Adjusted R ²	0.6097	Adjusted R ²	0.8771	Adjusted R ²	0.6423

T: Temperature (°C), R: Rainfall (mm), A: Area (hectare)

Table 3.6 indicates the effect of pearl millet (bajra) when cultivated in combination with other crops namely: maize, sorghum, green gram in Kharif season. The analysis indicates that the crop yield is supported by maize when cultivated in combination. However, the yield of pearl millet will reduce by 0.0003 kg/ha when cultivated with sorghum. Green gram will not affect the crop yield. Hence, it can be concluded that the crop combinations chosen by the farmer by his instincts and previous experiences contributes to provide an optimal crop combination.

Rainfall and temperature support the cultivation of pearl millet-maize and influence the pearl millet-sorghum and pearl millet-green gram cultivation. Green gram (moong) is cultivated as a subordinate crop in most of the districts of Rajasthan. The crop is quite sensitive to temperature and rainfall. The graphs 3.1, 3.2 and 3.3 illustrate the impact of area, rainfall and temperature on crop yield.

The following equations will determine the crop yield:

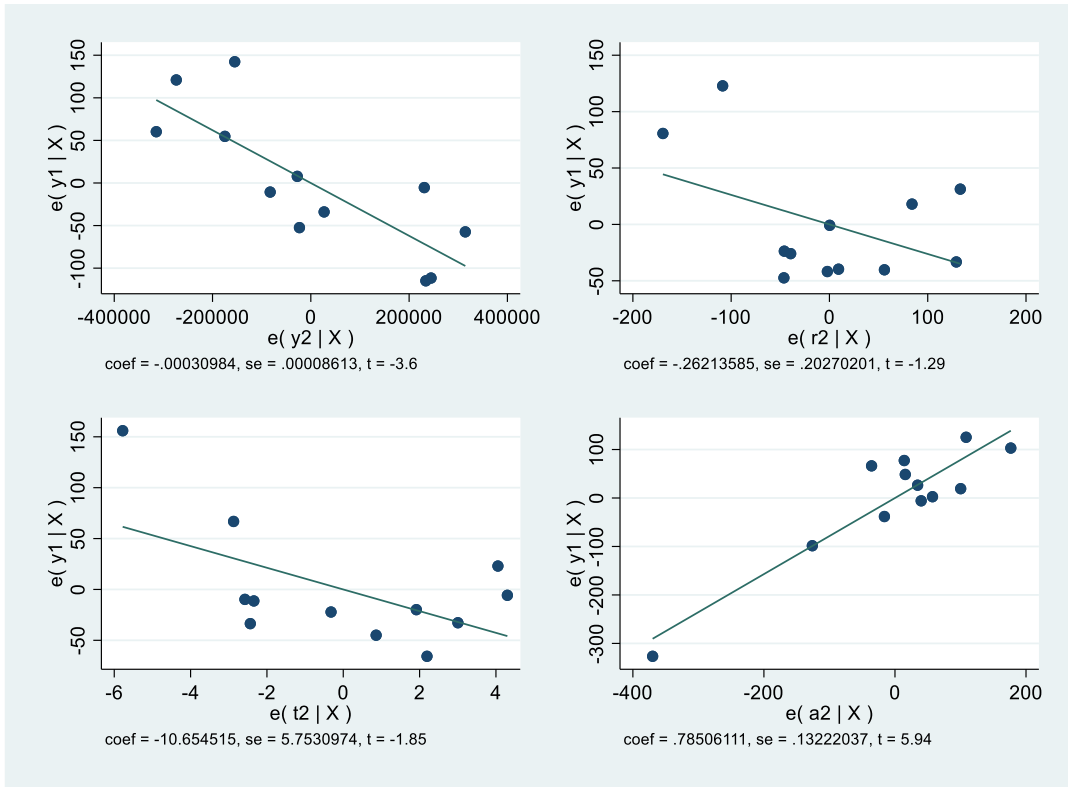
$$\hat{u}_{kit} \hat{u}_{jit} = x_{it} \alpha + \varepsilon_k + \varepsilon_j \quad (3.15)$$

$$\hat{u}_{kit} = f(x_{kit}, \beta) \quad (3.16)$$

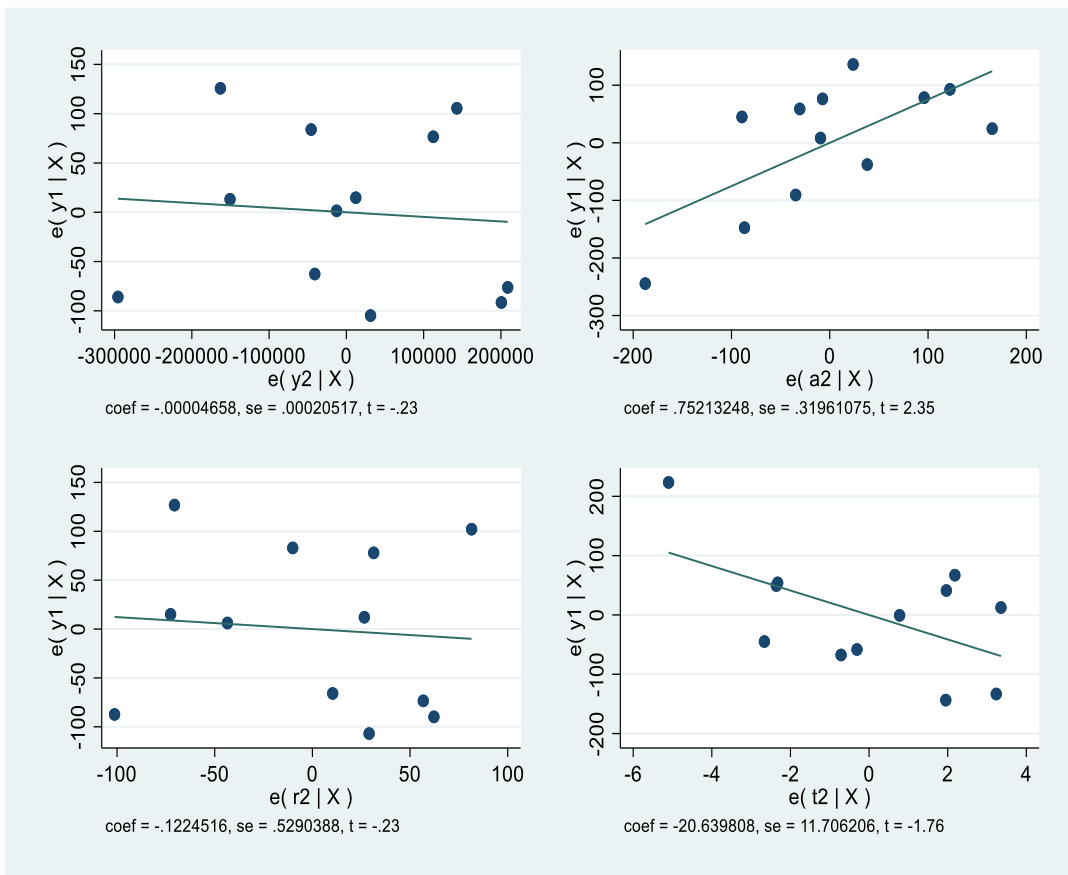
$$\hat{u}_{jit} = f(x_{jit}, \beta) \quad (3.17)$$

$f(x_{it}, \beta)$ denotes expected crop yield

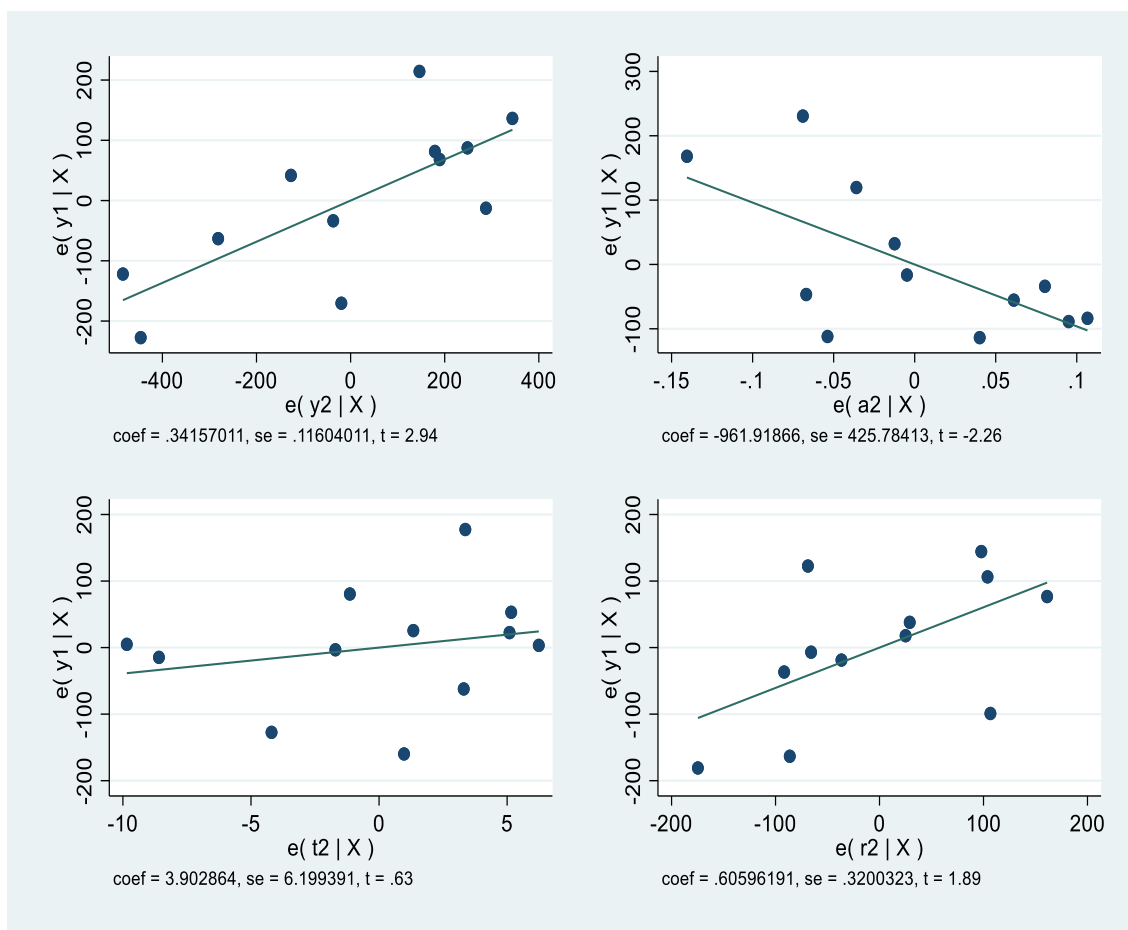
Since it is important to estimate that how the covariance among the crops is affected as a result of change in climate parameters (x_{it}). Thus, equation (3.15) is used to determine the covariance among the crops cultivated together in i^{th} season. Only linear form of covariance functional form ($x_{it} \alpha$) is considered for analysis. ε_k and ε_j represents the residual of j^{th} and k^{th} crops respectively (Isik & Devadoss, 2006).



Graph 3.1: Impact of Pearl millet on Sorghum



Graph 3.2: Impact of Pearl millet on Green gram



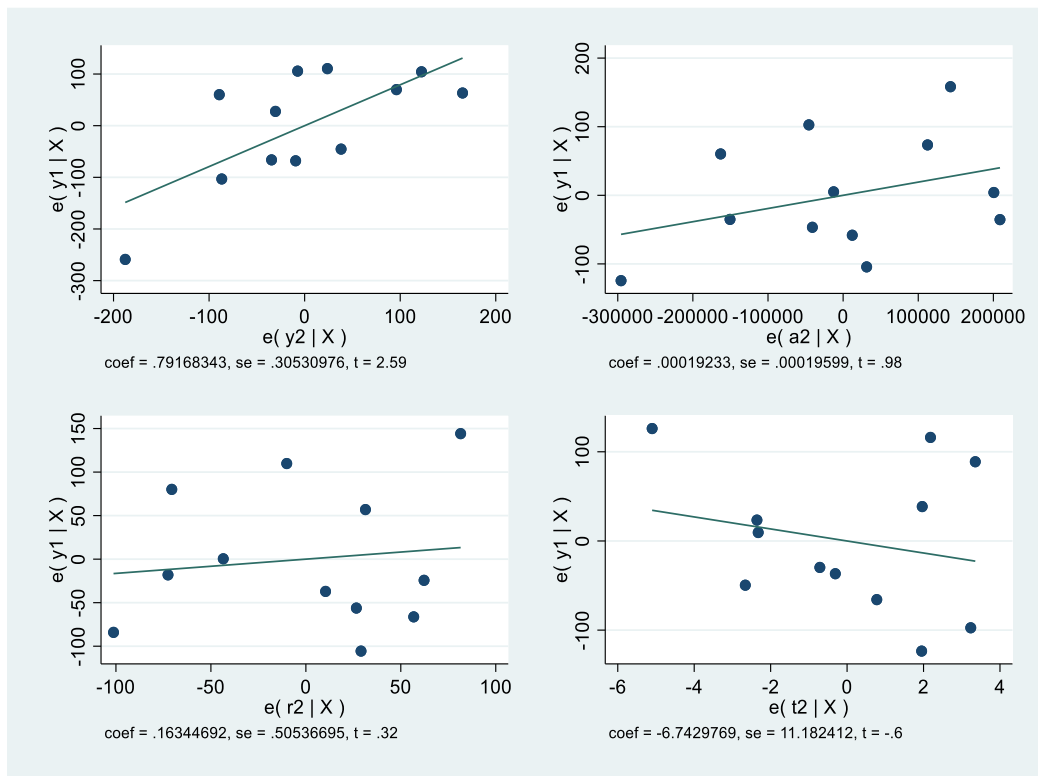
Graph 3.3: Impact of Pearl millet on Maize

Graph 3.1 indicates that only the area under each crop will improve the crop yield however, the remaining parameters negatively influence the crop yield i.e., reduces the yield. In case of pearl millet-green gram (Graph 3.2) combination, the temperature and area allocated under each crop favours the crop growth. The residuals of yield and rainfall are not significantly correlated to indicate the crop variance. Graph 3.3 shows that crop allocated is supported by climate parameters. From the analysis it is revealed that under the parameters considered pearl millet-sorghum and pearl millet-maize are the optimal crop combinations.

Table 3.7: Multiple Crop Choice Regression Model (Maize-Green Gram-Sorghum)

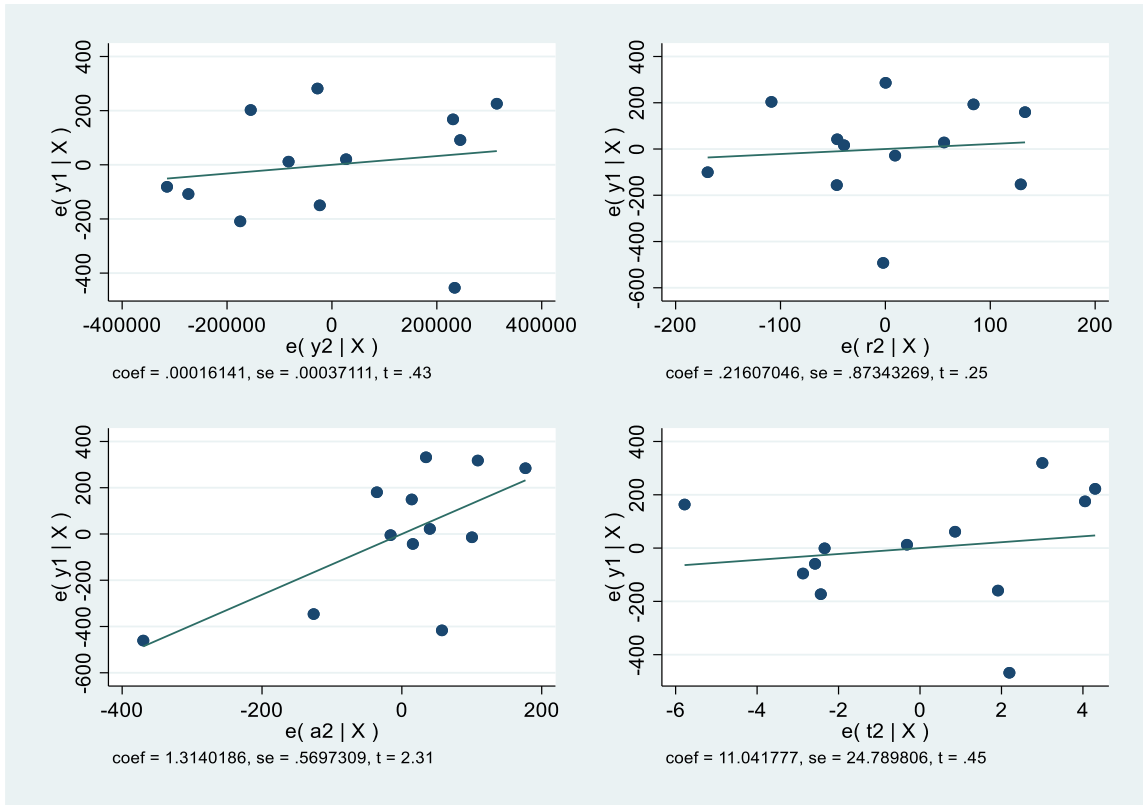
Sorghum		Maize		Maize	
Green Gram	0.7917	Sorghum	0.0002	Green Gram	0.0000
T	-6.7429	T	11.0412	T	-42.1051
R	0.1634	R	0.2161	R	-0.9113

A	0.0002	A	1.3140	A	1.5678
Coefficient of Determination	0.7520	Coefficient of Determination	0.4645	Coefficient of Determination	0.5796
Adjusted R ²	0.6103	Adjusted R ²	0.1584	Adjusted R ²	0.3394

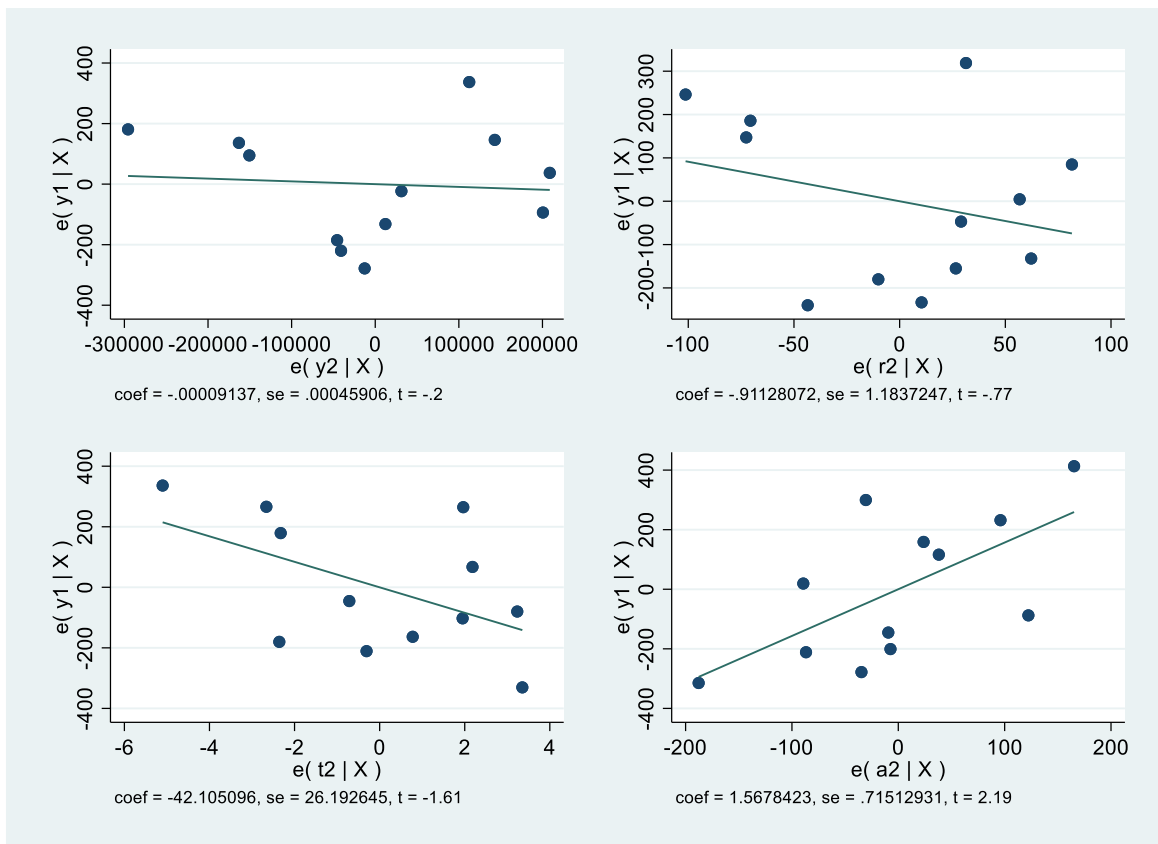


Graph 3.4: Impact of Sorghum on Green Gram

Graph 3.4 shows the effect of crop yield when sorghum and green gram are cultivated together. Crop yield, area and temperature supports the cultivation when allocated together. The temperature above a threshold value affects the crop yield of both crops. In case of maize-sorghum (Graph 3.5) the yield is supported by all the parameters. The data set plotted for maize-green gram (Graph 3.6) reveals that the combination is not an optimal choice as it is observed that the yield is sensitive to climate fluctuations and thus, increases the risk-parameter. Though many of the researchers consider risk as one of the parameters for mathematical model.



Graph 3.5: Impact of Maize on Sorghum

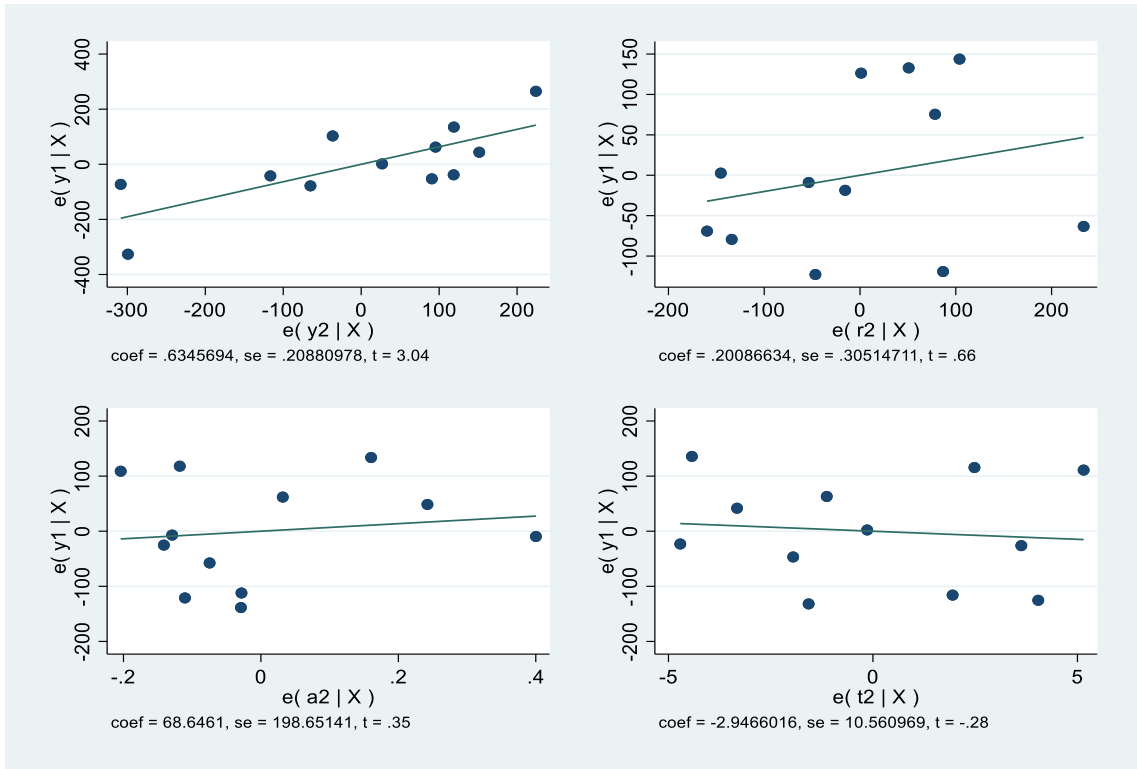


Graph 3.6: Impact of Maize on Green Gram

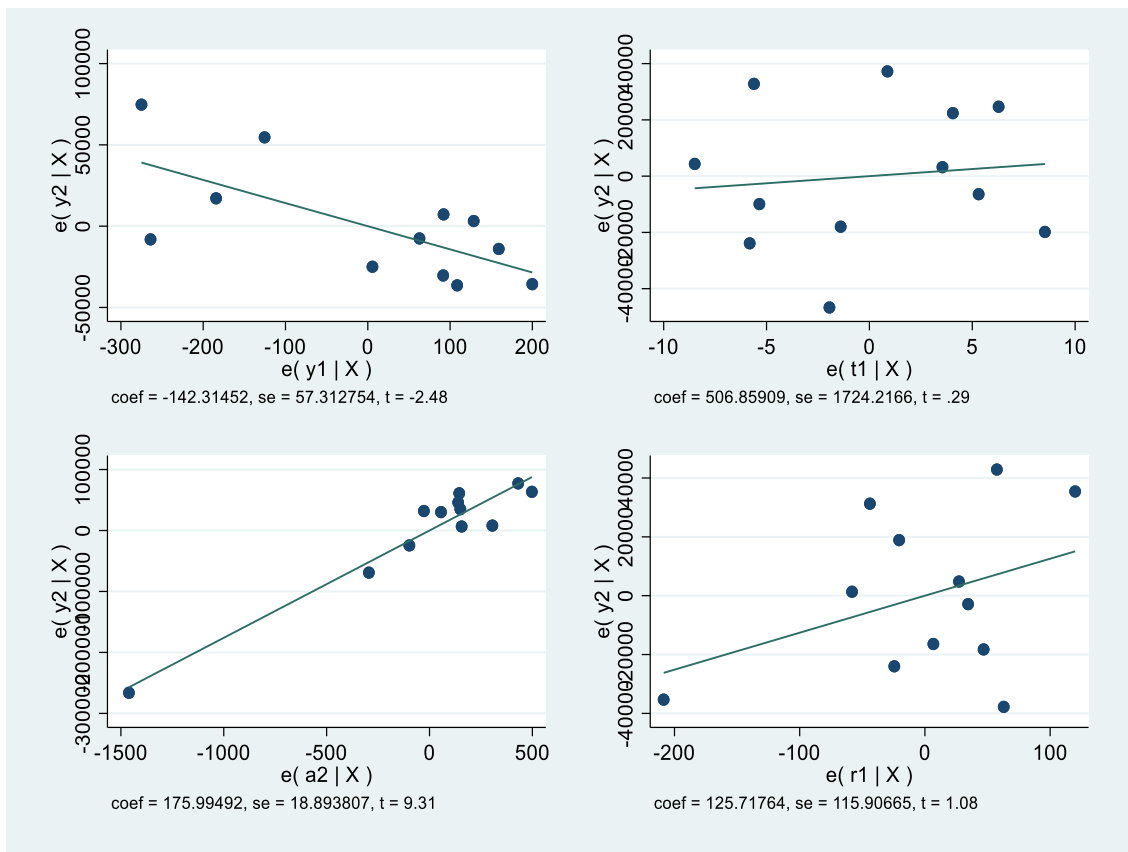
Table 3.8: Multiple Crop Choice Regression Model (Rabi season)

Wheat		Wheat		Barley	
Mustard	1.1538	Black gram	0.0000	Wheat	-142.3145
T	16.4251	T	0.6794	T	506.8591
R	5.7362	R	-0.1624	R	125.7176
A	-410.6929	A	0.39264	A	175.9949
Coefficient of Determination	0.7162	Coefficient of Determination	0.2406	Coefficient of Determination	0.9669
Adjusted R ²	0.5541	Adjusted R ²	-0.1933	Adjusted R ²	0.9479

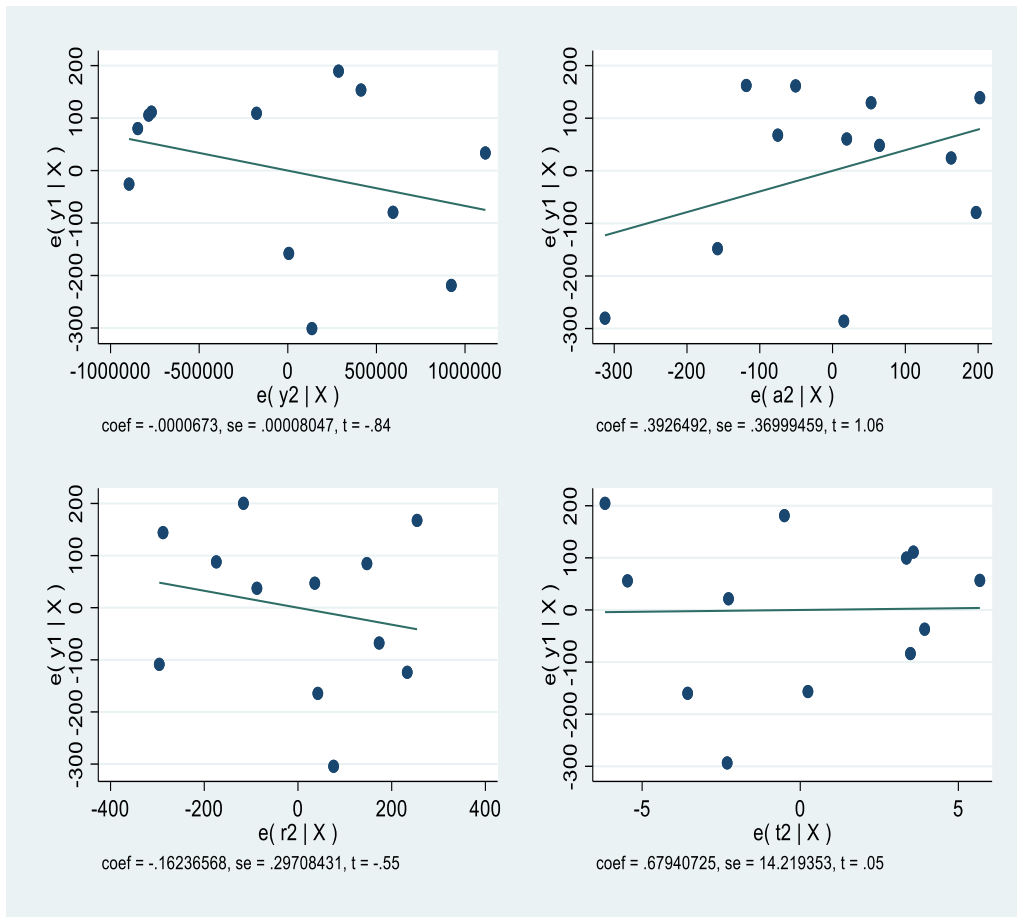
Impact of rainfall and temperature on wheat, cultivated in Rabi season is illustrated in Table 3.8. The wheat-mustard crop combination supports the crop yield, wheat-barley when cultivated together reduces the output and when wheat is cultivated with black gram there is no effect on yield. Both climate parameters play a significant role in crop improvement however, for wheat-black gram it leads to the reduction in yield with the increase in precipitation level. The graph below shows the effect of one crop over the other.



Graph 3.7: Impact of Wheat on Mustard



Graph 3.8: Impact of Barley on Wheat



Graph 3.9: Impact of Wheat on Black gram

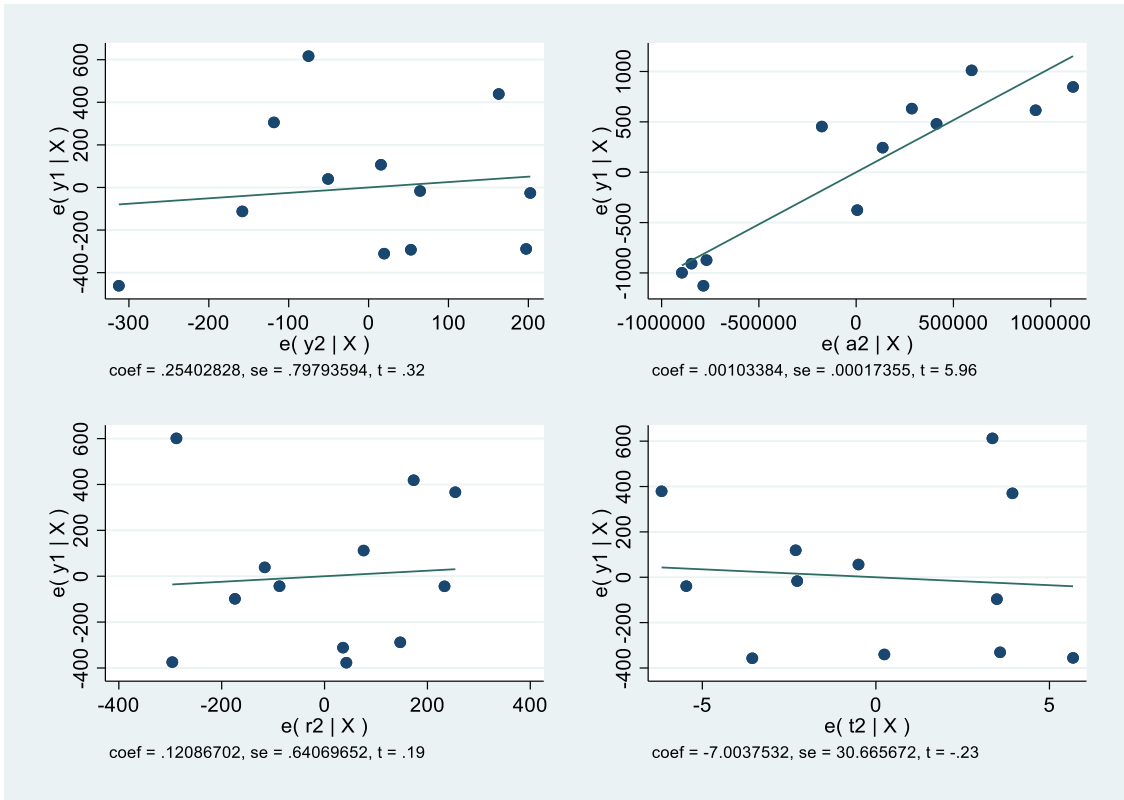
In Rabi season the commonly cultivated crops in districts of Rajasthan includes: barley, wheat, mustard and black gram. The farm considered allocate the field with these crops. The graphs represent the effect of wheat on the crops with which it is cultivated. Graph 3.7 shows that except temperature all the parameters support the crop yield. In wheat-barley and wheat-black gram combinations (Graph 3.8 and Graph 3.9) the yield shows a negative covariance thus, it can be depicted that the combination does not support each other. Though, the addition of some other parameters such as surface flow, soil features, labour may support the yield if considered. Hence, we say that the wheat-mustard is an optimal combination among all the combinations.

Table 3.9: Multiple Crop Choice Regression Model (Barley-Mustard-Black Gram)

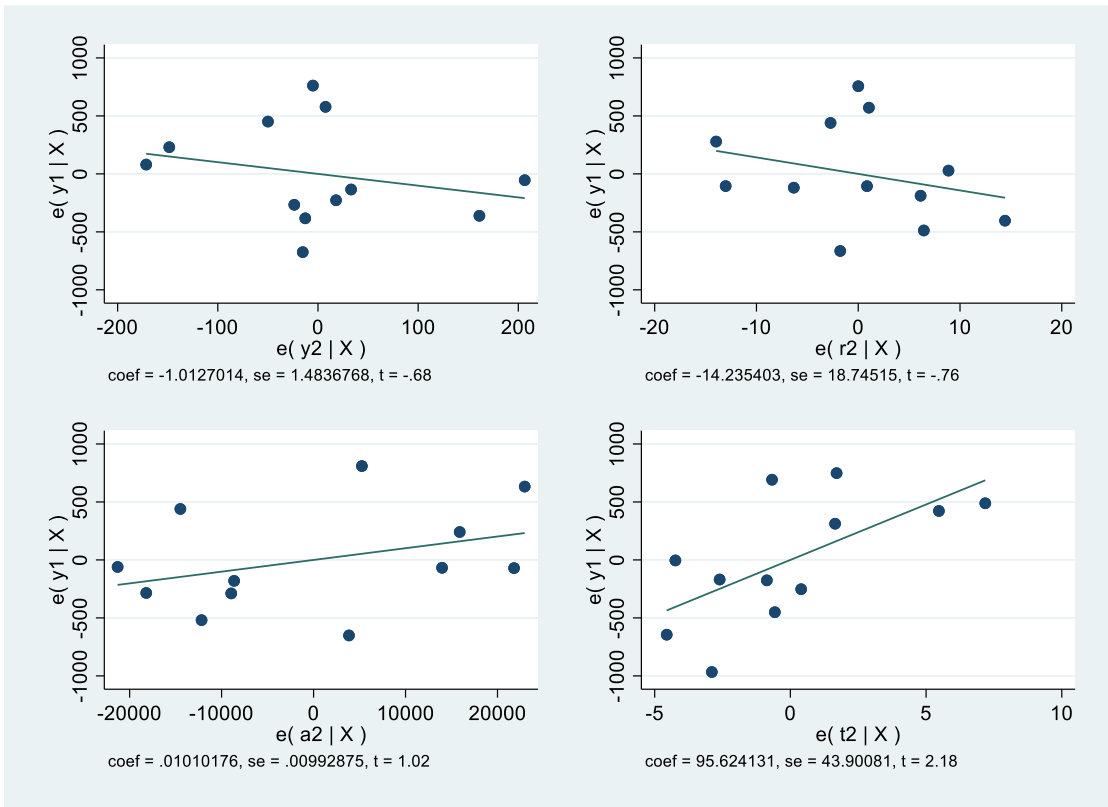
Barley		Barley		Mustard	
Black gram	0.2540	Mustard	-1.0127	Black gram	0.7196
T	-7.003	T	95.6241	T	-2.2233

R	0.1208	R	-14.2354	R	-0.1888
A	0.0010	A	0.0101	A	0.0000
Coefficient of Determination	0.8389	Coefficient of Determination	0.7313	Coefficient of Determination	0.8021
Adjusted R ²	0.7469	Adjusted R ²	0.5778	Adjusted R ²	0.6891

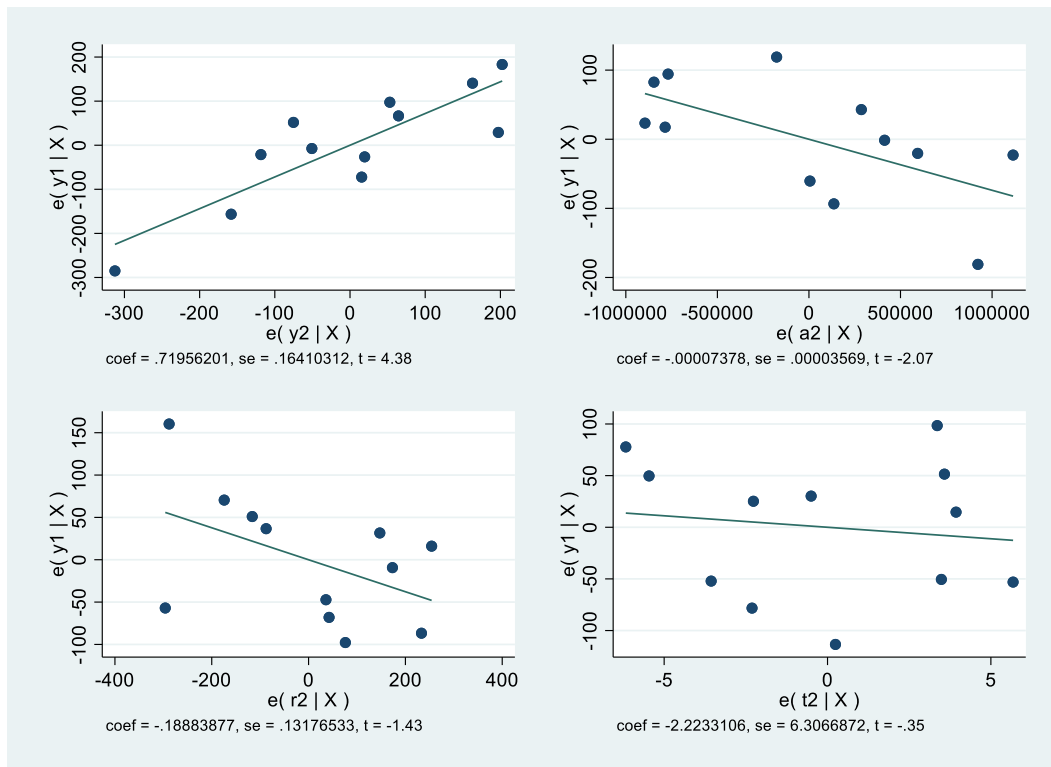
The crop combinations considered in table 3.9 revealed that the barley-black gram and mustard-black gram when cultivated together contributes to increase the crop yield and barley-mustard reduces the yield by 1.0127 units. The combination of barley-black gram and barley-mustard shows (Graph 3.10 & Graph 3.11) that a yield is affected by certain fluctuations in rainfall and temperature both. However, mustard-black gram shows a good fit measure (Graph 3.12). The combination has positively impacted each other to enhance the yield. (Verma, 2020) investigates the impact of climate parameters on gram yield. The result of statistical analysis shows that sudden rise in maximum temperature reduces the yield.



Graph 3.10: Impact of Barley on Black gram



Graph 3.11: Impact of Barley on Mustard



Graph 3.12: Impact of Mustard on Black Gram

3.4 Discussion

At different stages of crop growth crop response differently to the weather changes. Thus, the extent to which crop yield get influenced depends not only on the magnitude of weather parameters but also, the pattern of climate distribution over the region. This calls for dividing the whole crop season into finite intervals. Consequently, result in increase in the number of climate parameters that makes the scenario complex to evaluate the output.

However, linear regression models have been widely used by researchers to evaluate the impact of meteorological variables on crop yields (Kukul & Irmak, 2018; Leng et al., 2016). For the model formulation the period from 2006-2018 is used to examine the relationship between the meteorological variables and crop yield. Data regarding climatic parameters were derived from India Meteorological Department (IMD). Only temperature and rainfall were considered for analysis. However, (Liang, 2018; Rosenberg, 1981; Rosenberg, 1982) investigates the impact of CO₂ and fertilizers on crop yield.

For evaluation a correlation between the climate parameters and crop yield are estimated followed by multiple regression analysis with the aim to obtain a robust regression equation with respect to the change in the time series data.

Within the range of climate variables, the relationship between crop yield and temperature or rainfall is approximately linear. The graphs indicate that the climate parameters impact the crop yield. However, weather is not only the source of variability in crop yields neither for formulations nor in farms (Chmielewski & Potts, 1995). So, it can be concluded that only some part of the yield, variability can be explained by climate parameters. (Fisher, 1924) developed a technique to evaluate the effect of weather distribution on crops. He assumed that the effect of change in weather variable on crop would not abrupt rather it follows polynomial function of time. He expressed the weather variable as an orthogonal function.

The graphs presented will determine the impact of decision variables both controllable (area) and un-controllable (temperature, rainfall) on crop yield. The analysis result indicates that the increase in area under crop will support the crop with which it is cultivated. However, some of the crops are sensitive to the climatic fluctuations thus, resulting in the negative coefficient values. The sudden change in temperature extremes i.e., minimum and maximum average values is critical for plant growth. For example, during the grain-filling stage in wheat if the temperature is more than 34°C it leads to the reduction in yield as it accelerates the leaf senescence (Senthold Asseng et al., 2011).

Thus, to determine the climate-yield relationship with better approximations and precision to account for shifting sensitivity to climate stress during crop growth, many researchers considered the climate predictor variables over monthly or seasonal periods. For our analysis too we considered the crop predictions over a season (Iglesias et al., 2010).

Thus, the formulated model in this chapter examines a grower choice for crop allocation across a wide spectrum of climatic changes. However, the crop-mix and crop combination model formulated will determine the optimal crop combination alternatives among the available set of crops as a dataset. The model considers all the possible set of combination that would be considered in a particular season. The study finds that the crop choice is highly sensitive to temperature and rainfall. Thus, farmers adapt the crop choice on the basis of the local conditions faced by them. For example, in Kharif season for the farm considered, sorghum-maize is an optimal crop combination. It is found that sometime the growers cultivate their farm with a single crop. However, in general the growers prefer crop cultivation in combination with other crop that are capable to respond to the sudden climate changes. These combinations provide more flexibility in managing their resources than growing a single crop.

We considered the crops that is commonly and majorly cultivated in a region, the alterations in the crop selection can be made. For instance, sesame and groundnuts can be considered as an altered crop in Kharif season and peas and some vegetable crops in Rabi season.

Moreover, section 3.3.2 formulated a farm constraint that is often faced by the farmers in a region. The lower and upper limits of the decision variables support the growers to allocate their resources within the feasible region. The model solution provides an optimal feasible solution satisfying the algorithm conditions of non-negativity and feasibility.

Since no such study has been carried out in this direction for the region under consideration, thus, analysis will provide a way to the farmers to increase the crop production and hence the farm revenue by adapting an optimal crop combination with mathematical approach. Understanding the effect on productivity, response to climatic variations is fundamental for mitigating agricultural risks within the context of generating optimal farm revenues. The analysis can be further improved, by using some more climate parameters such as humidity, evapo-transpiration.