CROPPING SYSTEMS

AN EVALUATIVE REVIEW OF LITERATURE

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January 1963
Price $1.00
The teaching of crop production at university level has been facilitated by the recent publication of an excellent text on crop ecology. While knowledge of crop ecology is essential to a comprehensive study of agronomy, an understanding of the application of these principles to crop production practices in the field is no less important. Many excellent books on crop production has been published in North America, and these have served a useful purpose to teachers, extension workers, and those engaged in agronomic research. It is natural that the authors of such books devote major attention to crops and situations with which they are most intimately concerned, not only because of their interests, but also because of the limitations imposed on a single publication in terms of length.

The majority of crop production texts used in Canada have been written in the United States. It is rather natural that the somewhat unique ecological situations and the very substantial body of experimentally derived information available in Canada should receive inadequate treatment in such texts. Furthermore, much of the empirical and experimentally derived information available is scattered about in reports and publications with rather limited distribution. Even if this information could be brought together, its usefulness would be limited unless it were integrated with other sources of information of a similar nature, and interpreted with a degree of understanding of the experimental conditions involved and the ecological situations encountered.

The author of this publication has several years of experience in teaching crop production, both at vocational and university levels, preceded by a successful period devoted to agricultural extension. His colleagues who have encouraged him to do this task, and who have had the opportunity of reading

* Crop Adaptation and Distribution by Carroll P. Wilsie.
  (W. H. Freeman and Co., San Francisco)
the manuscript, feel that he has performed an exceedingly effective job of compilation, integration and interpretation.

While this bulletin may be most useful to those engaged in teaching and extension, it also contains material of interest to those who are concerned with planning and execution of various types of agronomic experiments. In making this material generally available, it is our hope that others may find this publication as interesting and useful as we who have already used it.

S. B. Helgason
Preface

This study was originally undertaken in 1959 as an assignment during the course of the writer's M.Sc. program in Agronomy. During the intervening years, the few typed copies in the Department of Plant Science have frequently been referred to by both students and staff. Consequently, the writer was encouraged to re-edit the original draft and to reproduce additional copies.

Although reference has been made to crop rotation experiments conducted in many parts of the world, no attempt was made to mention all of the literature on this broad and inclusive topic. An attempt was made, however, to uncover basic principles, or vital links in the cropping chain, that have come to light from past experimentation and research. Because of the vastness of the world literature on this subject, some significant and noteworthy principles or links may well have eluded the writer. It is suggested that this report be viewed as an exploratory venture into this region of agricultural practice and research, rather than as a complete and comprehensive analysis.

The encouragement and wise counsel offered throughout the preparation of this paper, by Professor L. H. Shebeski, Head of the Department of Plant Science, and by Professor S. B. Helgason, also of the Plant Science Department, is gratefully acknowledged.

January 1963

L. B. Siemens
# Table of Contents

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreword</td>
<td>i</td>
</tr>
<tr>
<td>Preface</td>
<td>iii</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>iv</td>
</tr>
<tr>
<td>List of Tables</td>
<td>vii</td>
</tr>
<tr>
<td>List of Figures</td>
<td>vii</td>
</tr>
</tbody>
</table>

## PART ONE

### GENERAL REMARKS

1. A Historical Sketch
   - Developments in Europe
   - Developments in the United States
   - Developments in Canada

2. Crop Rotation: Benefits and Limitations
   - Benefits
   - Monoculture

3. Difficulties Encountered in a General Discussion of Crop Rotations
   - Climatic Considerations
   - Economic Considerations

## PART TWO

### SOME EFFECTS OF CROP ROTATIONS

4. The Influence of Crops on Each Other
   - Effects of Varying Sequences of Major Crop Classes
   - Effects of Legumes in a Crop Sequence
   - Effects of Grasses in a Crop Sequence
   - Effects of Varying Sequences of Grain Crops
   - Effects of Soil Moisture on Crop Sequence
Yield Effects Other than Moisture in a Dryland Sequence
Effects of Roots and Other Crops in Sequence

5 Effects of Crop Rotations on Soils 31
6 Weed Control Through Crop Rotations 35
7 Plant Disease Control Through Crop Rotations 38
8 Insect Control Through Crop Rotations 43
9 Effects of Crop Rotation on Crop Quality 46

PART THREE

CROP ROTATION STUDIES IN WESTERN CANADA

10 A Historical Review 49
11 Effects of Varying Degrees of Moisture Limitation on Crop Rotations 55
12 Studies with Continuous Wheat and Fallow, Grain Sequences 58
   Continuous Wheat
   Fallow Grain Sequences
13 Studies With Fallow, Grain, Forage Rotations 61
   Studies at Indian Head
   Studies at Whitefox
   Studies at Brandon
   Studies at Lacombe
   Summary and Conclusions
14 Management of Manures in Crop Rotations 69
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>PART FOUR</td>
<td></td>
</tr>
<tr>
<td>A CRITICAL VIEW - PAST AND FUTURE</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>A Suggested Direction for Future Research Soil Moisture Soil Nitrogen Complementary Forage Relationships Crop Sequence Effect of Straw on Soil Productivity Monoculture</td>
</tr>
<tr>
<td>Bibliography</td>
<td>82</td>
</tr>
</tbody>
</table>
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minimum and Maximum Yields of Four Crops when Each Succeeds Sixteen Different Crops in a Crop Sequence Study in Rhode Island</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>Yields of Wheat and Corn when Following four Species of Legumes</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>Average Wheat Yields Per Acre at Lacombe, Alberta, When Following Eleven Different Crops</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>Wheat Yields at Three Locations when Grown in Three Different Sequences</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>Eight Year Average Grain Yield and Net Returns from Eight Different Crop Sequences tested at Brandon</td>
<td>28</td>
</tr>
<tr>
<td>6</td>
<td>Nutrient Losses Resulting from the Cultivation of Six Soil Types in Western Canada</td>
<td>31</td>
</tr>
<tr>
<td>7</td>
<td>The Effect of Top Soil Loss on Corn Yields in Indiana</td>
<td>32</td>
</tr>
<tr>
<td>8</td>
<td>Average Number of Water Drops Required to Disperse Aggregates of Soil Exposed to Seven Different Cropping Sequences</td>
<td>33</td>
</tr>
</tbody>
</table>

# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crop Rotations Established at Six Western Canadian Experimental Stations</td>
<td>53</td>
</tr>
</tbody>
</table>
PART ONE

GENERAL REMARKS

Chapter 1

A Historical Sketch

Crop rotations appear as a natural and obvious component of the art and science of agriculture. Because the systematic rotation of crops is so unspectacular it is easy to take for granted the enormous contributions that enquiring men of past generations have made to food and fibre production by employing the practice we have come to know as "Crop Rotations". To view the observations of early students of plant nutrition and crop rotations as obvious and trivial would be a mistake, for by so doing one of the thrilling chapters in the history of scientific agriculture would be overlooked. Hence a brief chronological review of the evolution and development of crop rotations as an area of study seems in order.

Developments in Europe

One of the most perplexing problems for plant scientists of the 18th and early 19th centuries was the matter of plant nutrition. From where, and how did plants obtain their nutrients for growth? The continued search for the solution to this problem eventually led early investigators to a study of the effects of tillage and the effects of alternation of crops on plant nutrients, which were measured in terms of plant growth.

Classic among these early studies was the project of the Flemish chemist, Van Helmont who, in 1635 demonstrated in his experiment with a willow tree that the increase in weight arising from "the wood, bark and roots arose from the water alone"(20). In 1731, an Englishman, Jethro Tull, published "The Horse-Hoeing Husbandry" in which he taught that the small particles of soil (pabulum) were the food of plants, and that the problem of nutrition could be solved by tillage through which the soils were made fine. Tull also invented the grain drill and the cultivator, which he called the horsehoe.
Senebier established the facts of photosynthesis in 1782 by proving the fixation of carbon from the carbon dioxide of the air. He was quick to point out that the increased weight of Van Helmont's tree came from this source.

It was not until 1794 that the French scientist, Antoine Lavoisier (40A) showed that plants and animals used oxygen and survived by the "burning" of organic food. The French agriculturalist, J. B. Boussingault (40A) was also working on the nutrition problem and he made his main contribution in 1834 by being the first one to use the field plot methods, rather than the laboratory pot method, for conducting his nutrition studies.

However, the great change in agricultural theory came in 1840 when a German scientist, Justus Von Liebig, published his findings (40A). He made careful analyses of surface soils and plants and explained the balance sheet of plant nutrition: "The crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substances conveyed to it in manure". Thus Von Liebig laid the cornerstone around which Soil Science has continued to develop. The big unsolved plant nutritional problem at this time was the source of plant nitrogen. Von Liebig theorized that all plant nitrogen was extracted from the air.

In 1842, John B. Lawes, a proprietor of the Rothamsted estate and founder of the Rothamsted Experimental Station, took out a patent for the manufacture of superphosphates and introduced artificial manures to agriculture. This was inspired by Von Liebig's findings. The following year Lawes persuaded a student of Von Liebig's, Dr. Joseph Henry Gilbert to join him. Together they set up a series of crop sequences and rotations in the hope that thereby they could learn more about the source of plant nitrogen. This was the year (1843) that the first crop of continuous wheat was harvested from the famous Plot 3 of Broadbalk farm at Rothamsted.

By this time, however, the idea of systematically rotating crops was not new. The famous "Norfolk rotation" first practiced by the Dutch had been popularized in the 1790's by Charles Viscount Townshend and Thomas William Coke, Earl of Leicester. This four year rotation - wheat, turnips, barley
and clover - was somewhat modified by Arthur Young who wrote in 1792, "Hence then some courses (rotations) arrange themselves that are applicable to all the soils of the world". Two examples of such rotations were: (a) roots, wheat, grasses, wheat; and (b) roots, wheat, grasses, pulse or maize, hemp or flax, wheat. In these rotations the main effect on soil productivity was found to lie in the number of years the grasses were left down. The records indicate that, "with the crop rotations begun in the Norfolk system, wider use of farm manures and improved tillage, wheat yields had risen by 1850 to 16 bushels an acre in Germany, 14 in France, and 20 in England" (40A).

**Developments in the United States**

Early soil management in the United States was largely copied from Western Europe. However, practices of Western Europe did not meet expectations in America because of different climatic and soil conditions. American agriculturalists soon learned that in order to obtain reliable information on cropping practices for their own country they would have to establish experimental rotations and fertility tests on their own soils. Thus, in 1876 George E. Morrow established the famous Morrow plots at the University of Illinois. They are the oldest agricultural experimental plots in America. In these plots corn has been grown continuously in rotation with oats, and in rotation with oats and clover since 1876. By 1882, relatively extensive field experiments were begun at the University of Pennsylvania where W. H. Jordan started the rotation of corn, oats, wheat and hay. Several rotations were started at the University of Missouri in 1888 by Sanborn and Waters. C. E. Thorne of the Ohio Agricultural Experiment Station laid out two rotations in 1894: a five year rotation of corn, oats, wheat, clover and timothy; and a three year rotation of potatoes, wheat and clover. Closely related to crop rotation studies is the classic work with flax by Dr. H. L. Bolley of the North Dakota Agricultural Experiment Station (20). He proved in the 1890's that the invariable failure of flax grown on "old land" was caused by a fungus disease, flax wilt, and not by an exhausted and infertile soil as was previously believed. By this time, crop rotations as a field for investigation was generally accepted by most agricultural research stations in the U. S. A.
Developments in Canada

Canada, being a younger country with a less rapid rate of development was somewhat later in its entry into agricultural research. Although the Central Experimental Farm in Ottawa was established in 1886, and the first regional stations in 1887 and 1888, Hopkins and Barnes (40) reported that it was not until 1911 that the Dominion Experimental Farm system established a comprehensive experiment to test the value of different types of crop rotations on its various Farms in the prairie provinces. This should not imply, however, that there was not a realization of the value of crop rotations or of the need for research in this area prior to 1911. In the 1893 annual report for the Experimental Farm for Manitoba (Brandon), Superintendent S. A. Bedford reported the following under the heading of crop rotations (3):

"At present very few farmers in this country practice a rotation of crops, many following wheat with wheat until the land is so impoverished or made foul with weeds that less than half a crop is obtained. As this system, or rather want of system, will have to be changed before many years, some experiments were undertaken this year for the purpose of throwing light on the proper rotations for this country. It will be seen that both fodder corn and millet stubble gave better returns than summer-fallow, this however, is the result of only one year's test."

It is interesting to note from the following quotation in Bedford's report of the year 1900 (4) that during the previous year (1899) he received a directive from Ottawa to plan a series of crop rotation studies:

"Last year, in accordance with your instructions, arrangements were made for a series of rotation plots, the principal object in view being the maintenance of the fertility of the soil, by ploughing under a leguminous crop every third year; instead of the usual summer-fallow."

In the same report Bedford records six years' data for a series
of rotations beginning with the year 1895. Ever since this early beginning the Brandon Experimental Farm has been active in crop rotation studies. On most other Western Canadian Experimental Farms, crop rotation experiments got underway between 1910 and 1912 (31, 40). At the University of Manitoba, Professor J. H. Ellis laid out an extensive crop rotation project in 1919. Champlin refers to rotation studies at the University of Saskatchewan as far back as 1922 (9).

Although the recorded history of crop rotation studies goes back just over a century, and although volume upon volume of data and findings are recorded in the literature, few conclusions of a fundamental nature have as yet been drawn. Because of the dynamics of this broad and general field of study, and because of the interaction of living creatures - from bacteria to man - there may be but a limited number of authoritative conclusions that can be recorded with finality and that can be depended upon to apply in all instances.
Chapter 2

Crop Rotations: Benefits and Limitations

Many attempts have been made to define a crop rotation. One acceptable definition is that a crop rotation is a planned sequence or order of crops grown in recurring succession on the same area of land.

Benefits

The advantages of following a planned sequence or order of crop production on the same piece of land are often taken for granted because they appear so obvious. A summary of these advantages, as listed by Wilson and Meyers (87), follows. Most of these items are dealt with in considerable detail in succeeding chapters.

(1) Soil fertility is better maintained. Growing the same crop on the same field continuously would inevitably deplete the soil of the particular nutrients required by the crop in question.

(2) Weeds, insects and diseases can be more easily controlled. Most insects and diseases require specific crops to feed upon, and therefore, by continuously planting a field to the same crop a serious buildup of the destructive organisms could result.

(3) Farm labor is better distributed. On a grain farm there are two peak periods of labor requirement - at seeding time and during harvest. By rotating grain crops with forage crops and by feeding livestock farm labor requirement would be more uniformly distributed throughout the year.

(4) Legumes, properly inoculated, help to maintain soil fertility.

(5) Diversifying crop production spreads the risk inherent in a single crop program.

(6) A planned sequence of cropping enables the most efficient use of farm and commercial fertilizers.

(7) Organic matter content of the soil may be maintained by plowing under crop residues.
(8) Increased organic matter and fibre content by means of crop rotation assists in controlling wind and water erosion of soil.

(9) Crop rotation improves crop quality. In most cases crop yield and quality are positively correlated.

Monoculture

From the nine points listed it would appear that following a planned sequence of crop production on the same land was advantageous in all instances and from all possible standpoints. This, however, is not necessarily the case. In discussing "Cropping Systems and Soil", in the 1957 U. S. D. A. Yearbook of Agriculture, "Soil", Allaway presents an interesting case for monoculture, or continuous cropping, under specific conditions and circumstances. Some of his points are summarized below:

(1) Although there are few time honored examples of successful monoculture, recent advances in the science of soil fertility might cause us to reconsider monoculture as an accepted farm practice - under certain circumstances. In the more humid areas the poor showing of monoculture, when growing non-legume crops continuously, was nearly always because of a lack of soil nitrogen. Since the Second World War nitrogen fertilizers have become abundant and relatively low in cost. Thus, the nitrogen problem could be overcome.

(2) If, for reasons of business organization it seems desirable to produce different kinds of crops on a farm with different kinds of soil, a monoculture system may permit each crop to be grown continuously on the soil best suited to its requirements. Thus, the steep soils, where erosion is a hazard may be kept in forage crops permanently, while the inter-tilled row crops continue to occupy the better gently sloping soils. Similarly, areas that drain and dry slowly could be used continuously for crops that do not require early spring field operations; droughty soils could be used for drought-resistant crops, such as sorghums, or winter small grains.
(3) The fertility level of the soil can be adjusted to fit one crop more readily and precisely than it can be adjusted to fit all the crops in a rotation. In areas where liming is necessary, under monoculture, each field could be limed to meet the optimum pH level for a particular crop. With chemical fertilizers each field could be maintained at the optimum fertility level for the particular crop it produces.

(4) Systems based on continuous cropping generally offer greater flexibility in planning the cropping system to meet year to year changes in the need for various crops. Part of the acreage can be shifted from one crop to another without upsetting the cropping plan of the whole farm.

The author does, of course, recognize several weaknesses in his case for monoculture, such as the problems of soil structure, pest control, etc. However, he suggests that pests might be controlled by suitable chemicals. Allaway does concede, though, that crops like peanuts, potatoes and bright leaf tobacco have rarely been grown successfully by monoculture. On the other hand, continuous cropping of sugar cane is the rule rather than the exception, while soybeans, rice, cotton and wheat have traditionally been cropped continuously or alternated with one year of fallow in relatively large areas of the world including the United States and Canada.

In summary, monoculture is not being advocated as a cropping system that should be generally adopted, but it is presented as a system having enough to commend it to have its possible merits investigated more closely, especially in the light of recent scientific advances in soil nutrition, pest control, etc. Monoculture, as a possibility, is also presented to caution those who readily accept all the merits attributed to crop rotations and who apply all these merits to all circumstances at all times.
Chapter 3

Difficulties Encountered in a General Discussion of Crop Rotations

Agronomists well recognize the many complicating factors that arise when one attempts to evaluate data and conclusions from crop rotation studies. Questions are often asked about the validity of data obtained from location A, for location B. These questions are usually justified because of the numerous interacting factors that make up the total environment of any particular soil area.

Thus, data and information obtained from a crop rotation experiment conducted at a particular location does not add greatly to the storehouse of knowledge unless the design of the experiment was statistically acceptable and unless a detailed account of soil and climatic studies of the past do not contain enough of this essential environmental information to make the data very meaningful or useful.

Climatic Considerations

Chen and Arny (11) reported that from 30 years' crop rotation data at the Agricultural Experiment Station, University of Minnesota, involving corn, oats, wheat and hay, the correlation coefficients indicated that on the average each of these crops reacted similarly to precipitation and temperature under different systems of cropping during any given period of time. However, different crops within a rotation reacted differently to varying moisture and temperature conditions. For example, oats showed a highly significant positive correlation coefficient between yields and precipitation during the flowering period (June 1 to July 10) and an even more highly significant positive correlation coefficient between yields and temperatures during the latter part of the oat growing season. Although the reaction of wheat was in general similar to that of oats, no significant correlation between yield and precipitation during the flowering period was found. Corn, on the other hand, showed a significantly positive correlation with the annual precipitation ending September 30th, but did not respond in yield to precipitation of any other period of the year or to accumulated heat units of any period during its growing season. Hay yields showed highly significant correlation coefficients with annual precipitation and rainfall from May to July. All correlation coefficients between hay yields and accumulative heat units
at any period of time were negative. Precipitation appeared to have a greater effect on hay yields than did temperature.

These correlation studies would indicate that year to year yield differences within a particular crop rotation could be influenced by temperature and moisture relationships, and thus interfere with the actual effect that the crop sequence under study had on the yield. Thus, environmental influences of this kind should be kept in mind when evaluating crop rotation data.

Economic Considerations

Another problem that usually arises when one attempts to evaluate data from crop rotation studies is the incomplete or out of date information on the economic implications of one rotation as compared with another. In discussing "Economics of Cropping Systems" in "Soils", the 1957 U. S. D. A. Yearbook of Agriculture, Earl O. Heady says,

"Two sets of forces determine the most profitable rotation or cropping system for a farm: Physical considerations, which determine crop yield possibilities, and economic considerations, particularly the prices and costs of the products."

However, in the final analysis economic aspects alone often determine the cropping system a farmer will select for his farm. Scoville, also writing in "Soil" says that although,

"the over-all objective of most farmers is to manage farm resources in a way that will return maximum income, this aim varies among individuals in a number of ways........ A young farmer who is in debt and has a growing family is likely to be under heavy pressure for immediate income. His farm program may include exploitative cropping practices that will increase income now with a sacrifice of productivity in the future. A farmer with less pressing needs for immediate income may have an economic goal of sustained annual income, or he may wish to follow a cropping system that will build up the soil to enhance his cropping system that will build up the soil to enhance his income in later years."

Most rotation studies have had as their main objective the max-
imization of crop output consistent with good soil conservation practices. Few studies have dealt with variations within this main objective that would meet the specific needs of the two farmers mentioned above. In "The Economics of Crop Rotations and Land Use" Heady and Jensen (34) suggest a number of reasons why Agricultural Economics has an immediate bearing on the cropping patterns used on farms. Some of these reasons are summarized:

(1) Current uncertainties on the world political horizon suggest that cropping patterns may need to be geared to meet a variety of circumstances. In the event of war a rapid increase in high-calorie crops will be called for with a heavy drain on soil nutrients stored in an earlier period. In times of peace the emphasis will be on soil conserving crops.

(2) Governmental intervention in the marketing of farm products may result in sudden changes in cropping programs.

(3) Fluctuations in farm cost-price relationships over the last decade have provided a complex decision-making environment for farmers.

(4) Variations in farm rental agreements often require specific cropping practices.

The economic influences which help to determine crop rotations mentioned above emphasize the need for the development of basic principles which apply generally to crop rotations and crop production. Basic principles are necessary so that farmers can be flexible enough in their cropping patterns to adjust to changes in economic relationships between crops and still take advantage of the best crop sequences and conservation practices known under the prescribed circumstances.
PART TWO

SOME EFFECTS OF CROP ROTATIONS

Chapter 4

The Influence of Crops on Each Other

Effects of Varying Sequences of Major Crop Classes

A crop rotation was defined earlier as, "a planned sequence or order of crops grown in recurring succession on the same area of land". Thus, a crop rotation will attain its purpose only if sound and intelligent planning has gone into the sequence in which the given crops will appear in the rotation. The order in which crops should be arranged within a rotation will obviously depend on the objectives of the rotation and on the physiological and morphological characteristics of the various crops making up the rotation. The objectives of most crop rotations are to maximize per acre income, consistent with maintaining or even improving soil productivity.

Chilcott (73) classified crops under the three general headings - exhaustive, intermediate and restorative. He cautioned, however, that these terms were not to be taken too literally since all crops that are harvested and removed from the land might rightly be said to be exhaustive. No crop actually restores plant food to the soil unless it is plowed under as green manure. Nevertheless, certain crops leave the land in a less productive state after cropping than it was before. Such crops Chilcott designated as "exhaustive", and he included in this group wheat, oats, barley, rye and millet. The following list cites some of the factors believed to be responsible for the depressing effect some crops have on those which follow them:

(a) a reduction of the available plant food,
(b) increased growth of weeds, fungi, or injurious insects,
(c) a change in the physical condition of the soil, particularly its water content,
(d) a reduction in the quantity or activity of beneficial
lower organisms.

"Restorative" crops have the opposite effect. They leave the soil in a better condition for certain crops than it was before. Among restorative crops Chilcott mentioned corn, potatoes, beans, peas, clover, alfalfa, most cultivated crops and perennial grasses.

Variable responses to the effects of preceding crops are also known to exist within a major crop class. For example, among cereals, it is generally assumed that oats following wheat is a better sequence than wheat following oats. Two exhaustive crops may also react differently to the beneficial effects of a preceding restorative crop; e.g. wheat is known to respond more readily to the beneficial effects of a preceding corn crop than does oats. An understanding of the factors responsible for some crops being good preceding crops and other crops poor, has been the object of investigations by many plant scientists since the days of Virgil in 30 B. C.

Most studies have shown that for any given situation the reasons why certain plants produce either beneficial or injurious effects on succeeding plants are due to a complex interaction of one or more of a large number of factors, some of which have not yet been identified. Odland and Smith (57) illustrated from their classic crop sequence studies in Rhode Island how dramatic the effect of one crop on another can be. Their data, as summarized in Table 1, shows the minimum and maximum yields of corn, rutabagas, mangels and potatoes when following each of 16 different crops in 1930.

The authors did not find a consistent correlation between available nitrogen and crop yield (except in the case of corn). They noted, however, that the crops tested left behind them various degrees of soil acidity but concluded that the evidence was not clear enough to indicate any factor as sufficiently predominant to cause differences of the magnitude noted.

Ripley (73) concluded that yield differences due to the preceding crop in Western Canada could usually be traced
to the moisture requirement of the preceding crop. Thus, the cropping treatments under test at the Western Canadian stations ranked in order of benefit to the succeeding crops as follows: Summerfallow, corn, potatoes, peas, millet, oats, wheat. In Eastern Canada where moisture is not a limiting factor in crop production the preceding crop effect was entirely different. Under these more humid conditions alfalfa and red clover were the most beneficial preceding crops and oats, barley, sunflowers, corn and potatoes were less favorable. To illustrate further the strong influence of the local environment on the effect of a preceding crop, Hartwell, Pember and Merkle (33) concluded that (on acid soils), the state of acidity in which preceding crops leave the soil had a major influence on the crops which follow, whereas Ripley (73) found (on a neutral to slightly alkaline soil) that the slight variation in pH that may have been caused by different crops had no effect on the succeeding crops.

Table 1. Minimum and Maximum Yields of Four Crops When Each Succeeds. Sixteen Different Crops in a Crop Sequence Study Conducted in Rhode Island

<table>
<thead>
<tr>
<th>Crop</th>
<th>Minimum Yield/Acre</th>
<th>Maximum Yield/Acre</th>
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<tbody>
<tr>
<td></td>
<td>% of Preceding Crop</td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>76 bu. 71% Corn</td>
<td>108 bu. Oats</td>
</tr>
<tr>
<td>Rutabagas</td>
<td>417 bu. 46% Rutabagas</td>
<td>900 bu. Cabbage</td>
</tr>
<tr>
<td>Mangels</td>
<td>11.5 T 36% Mangels</td>
<td>32.1 T. Potatoes</td>
</tr>
<tr>
<td>Potatoes</td>
<td>324 bu. 70% Cabbage</td>
<td>466 bu. Squash</td>
</tr>
</tbody>
</table>

The above references suffice to demonstrate the absence of any consistent or universal effects that most preceding crops have on crops that follow them in a sequence. In most cases the complex of the particular environment determines these effects. Because of this lack of a consistent crop sequence behavior pattern, Agronomists are unable to make broad and general crop rotation or crop sequence recommendations. Simon (81) from Germany, attempted to place recommendations for
crop rotations on a scientific basis rather than on an empirical one. This author suggested that rotation advice to farmers be limited to a series of two year compatible sequences - so long as reasonable intervals were left before the same crops were again grown on the same soil. He defined a compatible or complementary sequence as one in which the preceding and succeeding crops were suitable from standpoints of climate, soil and farm management. From actual tests the author devised charts showing suitable sequences for 13 crops in 3 climatic and several soil zones of East Germany.

Obviously most crop sequence studies have been conducted under climatic and soil conditions representative of large agricultural regions. Thus, general information gathered from these studies would have some value and application for the regions in which they were obtained. The remainder of this section will be devoted to a review of literature dealing with the effects in a crop sequence of legumes, grasses, roots, grains and miscellaneous crops when grown under different environmental conditions.

**Effects of Legumes in a Crop Sequence**

"Theophrastus, 370 - 285 B. C., spoke of leguminous plants 'reinvigorating' the soil. He said 'Of the other leguminous plants the bean best invigorates the ground' and again, 'Beans are not a burdensome crop to the ground; they even seem to manure it because the plant is of loose growth and rots easily; wherefore the people of Macedonia and Thessaly turn over the ground with it in flower'" (73).

Ever since the days of Theophrastus observant crop husbandmen have noted the soil building properties of legumes and their resulting benefits to succeeding crops. Many instances could be cited in which legumes have benefited succeeding crops in a rotation. This well known effect is illustrated with unpublished data obtained by the Manitoba Agricultural College on fertile Fort Garry clay containing .35% nitrogen, and cited by Ripley (73). (Table 2).

The data in Table 2 indicate relatively small differences
Table 2. Yields of Wheat and Corn When Following Four Species of Grass and Four Species of Legumes

<table>
<thead>
<tr>
<th>Preceding Crop</th>
<th>Wheat (bu.)</th>
<th>Corn (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-legumes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meadow fescue</td>
<td>19.2</td>
<td>7.00</td>
</tr>
<tr>
<td>Brome grass</td>
<td>14.3</td>
<td>5.58</td>
</tr>
<tr>
<td>Western rye</td>
<td>19.9</td>
<td>6.29</td>
</tr>
<tr>
<td>Timothy</td>
<td>19.6</td>
<td>6.69</td>
</tr>
<tr>
<td>Ave. of non-legumes</td>
<td>18.2</td>
<td>6.39</td>
</tr>
<tr>
<td>Legumes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alsike</td>
<td>31.8</td>
<td>10.77</td>
</tr>
<tr>
<td>Red clover</td>
<td>31.2</td>
<td>11.02</td>
</tr>
<tr>
<td>Sweet clover</td>
<td>32.5</td>
<td>11.05</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>31.3</td>
<td>12.15</td>
</tr>
<tr>
<td>Average for legumes</td>
<td>31.7</td>
<td>11.24</td>
</tr>
</tbody>
</table>

4-year ave. yield per acre from succeeding crops

between the preceding crop effects of the four legumes. Ripley also reported that Lyon demonstrated a variable gain in soil nitrogen with different legumes grown in alternate years with barley and rye for a period of 10 years. With alfalfa the gain was 607 pounds per acre, alsike clover 595, red clover and alsike 577, red clover 532, sweet clover 420; with soybeans a loss of 42 pounds an acre and with field beans a loss of 100 pounds. Part of this variability might be explained by Simon (8) who found in legume crops a correlation between the root mass, yield of tops and the yield of the first succeeding crop. Of all the legumes he was working with, alfalfa and red clover had the best effect on succeeding crops. Ripley (73) listed the following four reasons for the beneficial preceding crop effects of legumes.

(a) increase in soil nitrogen,
(b) improved physical condition of the soil,
(c) increased bacterial activity and
(d) increase in CO₂ production in the soil.

This paper will not concern itself with a critical evaluation of these conclusions.
It should not be assumed, however, that legumes are beneficial preceding crops under all growing conditions. In arid and semi-arid regions where moisture is a limiting factor in crop production, legumes in a rotation have not proven beneficial to succeeding crops. Allaway (1) traced the cropping pattern east of the Rockies according to moisture availability. On dry land farming just east of the Rockies a grain-fallow sequence is common. In the Central Plains a continuous cropping to grain crops predominates, whereas in the central Corn Belt, where annual rainfall commonly exceeds the water used by crops, deep rooted legumes are often used in regular rotations. Hughes et al. (47) reported that under similar conditions of growth a good crop of corn required about 12 acre-inches of water, a good crop of oats about 9 inches while a crop of alfalfa grown under irrigation may pass 30 inches of water up through the plant tissues. The same authors also cited the root depth studies conducted by Weaver which substantiated the large water requirement of alfalfa. Weaver found the depth of the alfalfa root system to be from 15 to 20 feet, while sweet clover roots ranged from 5 to 8 feet in depth and red clover and white clover about 5 feet.

Table 3. Average Wheat Yields per Acre at Lacombe, Alberta, When Following Eleven Different Crops

<table>
<thead>
<tr>
<th>Preceding Crop</th>
<th>Yield of Preceding Crop</th>
<th>Yield of Succeeding Crop of Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summerfallow</td>
<td>8.75 T.</td>
<td>38.2</td>
</tr>
<tr>
<td>Corn</td>
<td>224.8 bu.</td>
<td>34.6</td>
</tr>
<tr>
<td>Potatoes</td>
<td>9.05 T.</td>
<td>29.8</td>
</tr>
<tr>
<td>Sunflowers</td>
<td>0.88 T.</td>
<td>29.2</td>
</tr>
<tr>
<td>Sweet clover</td>
<td>72.2 bu.</td>
<td>25.5</td>
</tr>
<tr>
<td>Oats</td>
<td>1.43 T.</td>
<td>25.2</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>33.7 bu.</td>
<td>23.6</td>
</tr>
<tr>
<td>Wheat</td>
<td>2.01 T.</td>
<td>22.7</td>
</tr>
<tr>
<td>Crested wheat grass</td>
<td>1.72 T.</td>
<td>22.5</td>
</tr>
<tr>
<td>Timothy</td>
<td>2.24 T.</td>
<td>21.8</td>
</tr>
</tbody>
</table>

Ripley (73) reported that Briggs and Shantz found the water requirement of small grains to be almost twice as much, and of legumes almost three times as much as the requirement for millets, sorghums and corn. Thus, in semi-arid regions it would
be reasonable to expect a lower crop yield following legumes than following crops with a lower moisture requirement. In principle Ripley confirmed this relationship by means of a crop sequence study carried out at Lacombe, Alberta, where the mean annual temperature was 36.0 degrees F. and the mean precipitation 17.18 inches. In most instances lower wheat yields were obtained following high water consuming perennial forage crops (Table 3). The above data from Lacombe does not deny that the yield of wheat was inversely related to the moisture requirement of the preceding crop. However, because of relatively low yields of alfalfa and sweet clover the previous year, (hence less moisture consumed) the yield of wheat was higher after these legumes than after wheat and oats respectively.

Martin and Leonard (47) noted that,

"In non-irrigated areas where the annual precipitation is less than 30 inches, alfalfa exhausts the subsoil moisture. Yields on land sown to alfalfa for the first time have declined abruptly after 4 to 5 years due to subsoil moisture depletion."

Thus the extent to which annual, biennial or perennial legumes may be profitably grown under semi-arid dry land farming become a matter of careful management from region to region and from farm to farm.

However, moisture requirement is not the only factor that determines the effect of a legume on a succeeding crop. Ripley also noted that in soils fairly rich in nitrogen, legume could exert a detrimental effect on succeeding crops by feeding heavily on the available phosphorous and potash, with resulting deficiencies of these minerals. Bell, Odland and Owens (5) of Rhode Island harvested higher yields of potatoes following non-legume crops than when following legumes. In such instance they found, however, that additions of potassium, calcium and magnesium produced small increases in potato yields.

Although legumes may have contributed more toward the maintenance of a permanent and productive agriculture than most other types of crops, there are, unfortunately, noteworthy limitations to their use that should be recognized.
Effects of Grasses in a Crop Sequence

The contribution of grasses to the prosperity and permanence of agriculture is beyond estimation or measure. Ellis (22) attributed the high level of productive organic matter found in virgin grassland soils to centuries of growth and decomposition of grass. During the past few decades a great deal of concern has been voiced about the rapid losses of organic matter from the soils of the Great Plains. This has led to concerted campaigns toward the periodic regrassing of all cultivated soils. Brown, Wyatt and Newton (7) studied the effects of cultivation and cropping on the chemical composition of some western Canadian prairie soils and summarized their findings as follows:

"If in 30 years, we have lost one-fifth to one-third of the organic matter from our soils, very soon we must start replacing, or at least maintaining it, possibly by grass or legume rotation. By including such crops as grass or legumes in a rotation, the organic matter can be replaced to some extent, and the physical condition of the soil can be improved."

A similar study with similar findings was made in 1925 by Shutt (79). He concluded that,

"Exclusive grain growing must give way to a practice which introduces in a rotation grasses and clovers if the humus and nitrogen content is to be maintained and the 'fibre' - the binding element of the soil - preserved."

Hill (37) also determined the organic matter and nitrogen losses that resulted from 40 years of continuous fallow, wheat cropping at three locations in Western Canada, but concluded - somewhat more optimistically, as follows:

"It appears that a cropping practice which includes wheat and summerfallow can be continued profitably for some time to come in Western Canada if soil erosion and weeds can be controlled."

With certain crops and under certain conditions the
the physical condition of the soil may bear a determining influence on crop growth. In the Rhode Island studies, Odland, Bell and Smith (56) usually found redtop to be a favorable preceding crop. This grass species caused the soil to remain well aggregated. A high state of soil aggregation was found to improve air and water relationships, and promote the development of a desirable microbial population. These authors observed that the yields of onions when grown in two year sequences with mangels, buckwheat, corn and redtop, were directly correlated with the amount of water stable aggregates in the soil. The authors reported that earlier studies at the same station revealed that the yields of onions following cabbage, mangel beets, rutabaga turnips and buckwheat were very low, ranging from 13 to 17 bushels per acre. However, when following mixed timothy and redtop grasses or redtop alone, onion yields of up to 412 bushels per acre were harvested. Differences of this magnitude could not be explained by any single factor. Eventually, after a lengthy process of elimination it was concluded that at least four interacting factors were at least partially responsible for such yield differences.

(1) Some plants cause increases in soil acidity which may influence succeeding crops. Redtop created less soil acidity than several other crops.

(2) Some crops including redtop were "generally" favorable preceding crops, timothy was usually intermediate while alsike and red clover were usually unfavorable preceding crops.

(3) The microbial population of the soil was found to be associated with certain crops, and influenced succeeding crops.

(4) Soil organic matter and water stable aggregates were related.

Redtop accumulated more organic matter and increased the size of soil aggregates, which generally had a favorable effect on succeeding crops (5, 33, 57). It should be mentioned that most of the plots of the Rhode Island tests received generous applications of fertilizer so that crop sequence effects,
other than nutritional, could be studied.

Although Table 2 clearly indicates that under semi-arid conditions, where nitrogen may be a limiting factor, the first crop following grasses is considerably poorer than when following legumes, studies in other areas have shown that the benefits of grasses may outlast the benefits of legumes. Patzold (58) observed this tendency when growing three different crops following (a) red clover, (b) 6 grass-red clover mixtures, (c) 6 pure grasses and (d) fallow. During the first and second year, the highest yields were obtained when following red clover. By the third year the preceding crop value of crops (b), (c), and (d) had overtaken that of red clover. Red fescue was a very poor preceding crop the first year, but by the third year it overtook red clover by 20 per cent. The author found that nitrogen rather than root weight was correlated with the preceding crop value of red clover and grasses.

Simon et al. (82) also observed that legume roots produced a strong initial but short-lived benefit to the yields of succeeding crops. Grass roots, he noted, produced observable benefits after two years. He concluded, however, that nitrogen enrichment had a stronger effect on succeeding crops than did soil structure. He also found that meadow fescue and perennial rye grass had good preceding crop value on dry sandy soils of East Germany. This finding further serves to point out the varying effects of different grass species on succeeding crops. In a survey of the wheat growing area near Christchurch, New Zealand, Miller (52) noted that significantly better yields of wheat were obtained from wheat following grass or from wheat as second crop after grass than from wheat after two or more years of other crops.

The main value of grass in a cropping system lies in the extensive root system of the plant (7, 22). However, crops immediately following grasses in pure stands, usually tend to yield poorly under black earth conditions (73). Hedlin et al. (36) obtained a 34.4 bushel per acre yield of wheat when following alfalfa and 25.6 bushels when following grass. He noted that an application of 16-20-0 fertilizer at 108 pounds per acre partly offset the depressing effect of grass on a succeeding wheat crop. These authors reasoned that the cause for the lower crop yields following grass was due to the
immobilization of nitrogen during the decomposition of grass residues. The authors found that with grass as a preceding crop wheat contained a lower protein content than when alfalfa preceded wheat.

Ellis (23) also observed the depressing effect of the cultivated grasses on the yield and protein content of subsequent wheat crops, but found that this effect was counteracted when alfalfa accompanied the grass in a mixture. Ellis attributed the depressing effect of pure grass stands on yield and protein content of wheat to the wide carbon:nitrogen ratio of the grass roots and residues. As a conclusion to this study Ellis wrote as follows:

"This points forcibly to the conclusion that on the black-earth soils, the use of pure stands of grass alone in rotation cannot be expected to increase either the yield or quality of subsequent wheat crops. The reverse is to be expected. The beneficial effects of grasses on the physical conditions of the soil, and the necessity of using grasses more extensively for the prevention and control of soil drifting on arable soils is admitted and advocated, but the writer would strongly urge the necessity of using legumes in appropriate mixtures with grasses in order to maintain yield and quality in subsequent grain crops as well as to improve the quality and yield of forage and fodder. When grown for soil improvement, grasses and legumes must be combined if physical and chemical conditions of the soil is to be improved."

The above conclusion is generally accepted and has been verified by many workers in the area of crop and soil management.

Effects of Varying Sequences of Grain Crops

Grain crops are usually classified as "exhaustive" or "soil depleting" crops. They represent the cash crops in the rotation. This section will confine itself to the effects of different sequences of grain crops in a rotation. In a well planned crop rotation exhaustive and restorative crops should alternate when possible, and exhaustive crops should be arranged in a particular sequence (12). The best sequence for
grain crops is usually related to the major limiting factor to
crop production of the particular area. For example, on acid
soils with ample moisture, the sequence might be arranged in
descending order of lime requirements. On soils limed for
alfalfa, clovers or soybeans, the sequences might be as follows:
(a) alfalfa, sugar beets, barley, (b) alsike clover, corn, oats,
or (c) soybeans, potatoes, rye. Under semi-arid conditions on
the Great Plains the sequences might be arranged according to
the residual soil moisture left by the crops in question. Thus,
small grains usually follow corn in rotation because corn
leaves more moisture in the soil than do other grains (47).

Grain crops may be managed in several ways: they may
be seeded continuously on the same area of land; they may be
alternated with a rest or fallow period, or they may be grown
in a variety of sequences with other grains, roots, forages or
intertilled crops. The depressing yield effect of cropping
grain continuously has been observed at many agricultural
experiment stations. Dunham (20) reports the average yield
of wheat grown continuously for 63 years on the Broadbalk field
at Rothamstead at 12.7 bushels, on Haas field where wheat was
alternated with fallow the yield was 17.4 bushels, and on the
Agdell field where wheat was included in a rotation with turn-
nips, barley, legumes or fallow, and wheat, the crop averaged
25.5 bushels. He also stated that the average yield of corn
grown continuously for 74 years on the Morrow plots in Illinois
has been 27 bushels per acre; when alternated with oats, the
corn averaged 36 bushels per acre, and when grown in a rotation
of corn, oats and clover it yielded 51 bushels per acre. Moomaw
(54) of North Dakota, reported data from a 17 year study of
wheat, oats, barley and corn when grown continuously and when
grown in rotation with other crops. He found that yields of
all crops except corn were greatly decreased by continuous
cropping. Wheat yields reduced from an average of 18.4
bushels per acre in rotations to 12.7 bushels when cropped
continuously. Oats in rotation averaged 37.7 bushels and con-
tinuous oats yielded 27.5 bushels per acre. Barley in rota-
tion yielded 26.6 bushels, compared with 21.4 bushels when
grown continuously. Corn, on the other hand, showed a slight
increase in grain yield, but a decrease in yield of fodder when
cropped continuously. The author concluded that from all the
evidence at hand the decreased yields from continuously cropped
land resulted from an increase in weeds rather than a decrease
in soil fertility.
Obviously the relative merits of continuous vs. alternate cropping are closely related to annual rainfall. Foster (25) said there were many farms in Saskatchewan that have never grown anything but cereal grains (mainly wheat) since they were originally broken up. He then presented the following data from three experimental stations in Western Canada to illustrate the influence of climate on the effect of continuous cropping.

Table 4. Wheat Yields at Three Locations When Grown in Three Different Sequences

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Swift Current</th>
<th>Lethbridge</th>
<th>Lacombe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous wheat</td>
<td>8.3</td>
<td>12.4</td>
<td>30.1</td>
</tr>
<tr>
<td>Wheat, fallow</td>
<td>6.8</td>
<td>14.0</td>
<td>-</td>
</tr>
<tr>
<td>Wheat, wheat, fallow</td>
<td>6.9</td>
<td>13.4</td>
<td>27.2</td>
</tr>
</tbody>
</table>

Ave. Annual Precipitation  13.14 inches  15.84  17.73  
(1922-1946) (1902-1946) (1908-1946)

Swift Current reported frequent crop failures with continuous wheat. However, in years of higher rainfall the yields were similar to summerfallow yields. Investigators at Lacombe, when working on black and grey-wooded soils of Northern Alberta saw little justification for summerfallow but noted a rapid build-up of certain weeds, on the continuous wheat plot, notably wild oats. Foster concluded his observations as follows:

"These three stations represent three quite distinct soil and climatic differences. However, the yield data point out quite definitely that there could be quite a large reduction in the acreage of summerfallow without any loss of production, provided weeds and insects could be controlled. Wide variations in yield from year to year do not favor the use of continuous cropping in spite of the favorable average figures for this practice. The difficulty of controlling certain weeds under this system is also a deterrent to its widespread adoption."
That a gradual decrease in yield occurs when the same grain crop is grown continuously on the same soil has been found by a number of other workers (9, 11, 20, 40, 47). Most experimenters attributed a large portion of the yield decreases on continuously cropped fields to a build-up of weeds, insects or diseases. Thus, in the light of recent scientific advances several agronomists are beginning to re-assess their position toward the continuous cropping of certain crops. Herbicides, fungicides and insecticides are now able to control most crop pests, and fertility experts are now able to prescribe fertilizer requirements for most crops. Recent indications are that this line of reasoning is gaining some momentum, especially in the corn belt of the U. S. A. However, in a continuous grain cropping program matters like soil organic matter and soil structure would still demand careful attention.

The remainder of this section deals mainly with the effects of different crop sequences on a number of cereal crops under dryland farming conditions. Many workers suggest that, under dryland farming, soil moisture retention and annual precipitation are the dominant factors influencing the effects of different crop sequences (12, 23, 25, 46, 47, 49, 54, 60, 69, 73, 84).

**Effects of Soil Moisture on Crop Sequence**

Martin and Leonard (47) suggested that in general, agricultural areas with annual precipitation from 12 to 18 inches would need to follow a two year sequence of grain, summerfallow. With additional precipitation the number of crops in a sequence might be increased to two crops of wheat after fallow, or to wheat after corn.

Mathews and Cole (45) stated that crop rotations under dryland farming have some basic differences from rotations for more humid areas. They held that the maintenance of soil fertility is important at all times, but that under dryland conditions more attention should be placed on selecting suitable crops and arranging them in a sequence according to their moisture requirements. Ripley (73) verified this observation from data obtained at Swift Current. At this station the water requirements of corn and sunflowers were found to be 240 pounds and 375 pounds respectively. Basis a five year average, wheat following
corn yielded 29.8 bushels per acre, following sunflowers 14.9 bushels and after summerfallow 50.8 bushels per acre. The author of this study concluded rather obviously that the amount of moisture removed from the soil by a particular crop had a decided influence on succeeding crops.

From other soil moisture studies at Swift Current, Barnes reported the following "water requirements" of crops: (water requirement refers to the pounds of water required to produce one pound of dry matter). Wheat, (grain and straw) 375 lbs; barley, (grain and straw) 345 lbs; oats, (grain and straw) 326 lbs; corn 240 lbs; sunflowers 386 lbs. Ripley further substantiated the importance of the water requirements of preceding crops on the yields of the succeeding crops by referring to a twelve year crop sequence study conducted at Swift Current involving summerfallow, corn, peas, millet, oats and wheat. With very few exceptions the yields of the succeeding crops followed the order of the water requirements of the preceding crops. In most instances the succeeding crop yields decreased when following the crops in the order listed above. Ripley also found that under the more favorable moisture conditions prevailing at Ottawa, these same crops reacted very differently as preceding and as succeeding crops. Thus, there is no one crop sequence of a given number of grain crops that is best under all conditions. The optimum sequence must be established by experiment for each crop producing region.

Even within the Great Plains area Chilcott (12) noted a variable sequence reaction to three grain crops. In twenty-four out of thirty-five tests grown from Texas to North Dakota a sequence of corn-wheat-oats produced the best results. At the other nine stations the corn-oats-wheat sequence proved superior. Under climatic conditions in the Ohio Valley McIlvaine and Pohlman (49) found wheat yields to be significantly better when grown in a three year sequence following corn and preceding soybeans. Under Rhode Island conditions corn yields declined in the following order when succeeding the crops listed: Oats (81.9 bu.), buckwheat (77.7), millet (75.2), rye (74.4), corn (62.4). Obviously a soil factor other than moisture was responsible for the sequence relationships found best in the above two experiments.

Ripley's findings of the beneficial effects of corn
in a dryland crop sequence have already been mentioned. Thysell et al. (84) of North Dakota also found that small grains usually yield higher after corn than when following another grain crop. Data from the Morden, Manitoba, Experimental Farm (69) indicates that the average yield of 13 years of wheat after summerfallow was 34.7 bushels per acre compared with a yield of 35.3 bushels per acre for wheat after corn. This data closely parallels the findings of Ellis (23), who, under similar precipitation conditions obtained a 10 year average yield of 28.66 bushels per acre for wheat after fallow compared with 28.60 bushels per acre after corn. Workers at the Brandon Experimental Farm, where the long term annual precipitation is about 2 inches less than at Morden, found that wheat and other crops following corn yielded considerably less than when seeded on summerfallow (60). From a 22 year study at Brandon, wheat following corn yielded 19.4 bushels per acre compared with 28.8 bushels after summerfallow. Thus, under dryland farming conditions water requirements of preceding crops appear to have a determining effect on the yields of succeeding crops.

Yield Effects Other than Moisture in a Dryland Grain Sequence

Even under dryland conditions it is possible that factors other than moisture might affect the yields of succeeding crops in a cereal sequence. It is interesting to note that Schonbeck (76) observed that cold water extracts of cereal straw inhibited the germination of cereals, particularly barley. He also noted a depression of the root growth of wheat when treated with water extracts of cereal straw and roots. An addition of .15 per cent straw to the soil depressed root growth of young wheat plants by 23 per cent. The author found greater quantities of inhibitor substances under rows of stubble than between rows. Ebert (21), also of Germany, grew all combinations of oats, barley, rye and wheat as preceding and succeeding crops. He noted that preceding crops differently effected the water consumption, transpiration, nutrient content and grain yield of the crops which followed.

Although the effects of diseases and weeds on crop rotation will be discussed in later chapters, it appears that these pests have a direct bearing on the preference of cereal crop sequences under field conditions. Ripley's findings that crops in a dryland sequence yield in relation to the water
requirements of the preceding crops, have been mentioned. However, interesting deviations from this expected pattern were found at the Brandon Experimental Farm from a seven year comparison of varying fallow, grain sequences (61). Data from part of the experiment appears in Table 5.

Table 5. Eight Year Average Grain Weight and Net Returns From Eight Different Crop Sequences Tested at Brandon

<table>
<thead>
<tr>
<th>Crop Sequence</th>
<th>Ave. lbs. grain/A.</th>
<th>Ave. net returns/A.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fallow, wheat</td>
<td>1157</td>
<td>$11.70</td>
</tr>
<tr>
<td>Fallow, wheat, wheat</td>
<td>1302</td>
<td>12.57</td>
</tr>
<tr>
<td>Fallow, wheat, oats</td>
<td>1413</td>
<td>13.79</td>
</tr>
<tr>
<td>Fallow, oats, wheat</td>
<td>1430</td>
<td>13.79</td>
</tr>
<tr>
<td>Fallow, wheat, barley</td>
<td>1460</td>
<td>14.09</td>
</tr>
<tr>
<td>Fallow, barley, wheat</td>
<td>1546</td>
<td>16.92</td>
</tr>
<tr>
<td>Fallow, wheat, flax</td>
<td>1105</td>
<td>17.31</td>
</tr>
<tr>
<td>Fallow, flax, wheat</td>
<td>999</td>
<td>18.26</td>
</tr>
</tbody>
</table>

This experiment was conducted on a fertile clay loam soil. Ferguson (21) suggested that plant diseases were responsible for the lower production and net returns from the fallow, wheat, wheat and fallow, wheat, barley sequences, as compared to the better showing of the fallow, barley, wheat sequence. He further noted that a low weed infestation in the fallow, flax, wheat sequence was responsible for its heavier production than the more heavily weed infested fallow, wheat, flax sequence. Gerrie, White and Larter (29) showed that under Saskatoon conditions flax on summerfallow produced about one-third as many pounds grain per acre as wheat, and thus must return at least three times the price of wheat per pound to be competitive. The authors also found that wheat, barley and flax yielded similarly when following flax or wheat in a sequence.

Thus, no simple formula exists whereby one may make general recommendations as to the best cereal crop sequence to follow in a given region, or on a given farm. Conditions of soil, climate, disease, insect and weed control along with price relationships between crops, may all help to determine the best grain sequence for any given locality.
Effects of Roots and Other Crops in Sequence

Root crops are usually thought of as undesirable preceding crops, especially for roots and cereals (5, 15, 19, 33, 56, 57). At the July, 1920, Conference on Conservation of Soil Fertility and Soil Fibre, held in Winnipeg, Mr. F. H. Reed, Assistant Superintendent of the Brandon Experimental Farm stated in his paper (15),

"Field roots are much less effective than corn as a preparatory crop for grain, and sunflowers somewhat less effective, though better than roots".

This observation was confirmed by Dubetz, Russel, and Hill (19), when growing seven cash crops in all combinations under irrigation at Lethbridge for four years. In this study field beans proved the best preceding crop, with potatoes and canning peas in second and third place respectively. The least effective preceding crops were barley and sugar beets. However, preceding intertilled plots of sugar beets, corn and beans produced the least weedy succeeding crops.

Kemenesy (41), of Hungary, obtained similar results under the extreme continental climate of his area. Of the crops he studied in various sequences, he found alfalfa to be the best preceding crop and root crops the worst. As factors contributing to the complex of factors causing preceding crop differences, he listed, (a) soil moisture, (b) manuring, (c) state of harvest other than at maturity, (d) shade, and (e) density of root growth. Odland et al. (56) suggested that a few additional preceding crop effects of mangels existed under Rhode Island conditions. He reported that in 1924 Burgess showed that mangels increased the acidity and readily soluble aluminum content of the soil. It was later found that this situation, in addition to a poor physical condition of soil resulting from the culture of mangels, produced an ideal environment for a root-rot organism. This root-rot then partly explained the extremely depressed yields of mangels and other root-rot susceptible crops when following mangels in a sequence. Relief to this preceding crop effect of mangels was found by partially sterilizing the soil with Chloropicrin. However, following such a treatment onions and other crops sensitive to acid conditions, continued to yield poorly.
ing mangels because of the subsequent increase in soil acidity.

Potatoes, on the other hand, have often proved to be a beneficial preceding crop for grain and sugar beets, but not for a succeeding crop of potatoes (19, 45, 56, 73). Dubetz et al. (19) found potatoes to rank second to field beans of the seven crops compared as preceding crops at Lethbridge. However, the poorest succeeding crop yield of potatoes in the sequence occurred when following potatoes. The authors suggested that the beneficial preceding crop effects of potatoes were partly due to the improved physical structure and tilth in which they leave the soil. Odland et al. (56) also noted that potatoes did most poorly when following potatoes in a sequence. Leightly (45) referred to experiments that have shown sugar beet yields to be 70 per cent higher in an alfalfa-potato-sugar beet sequence than when the same crops were re-arranged in the order of alfalfa-sugar beets-potatoes. He found that potatoes yielded well following alfalfa, but that sugar beet yields following alfalfa were quite depressed.
Chapter 5

Effects of Crop Rotations on Soils

Most of the previous sections of this paper make direct or indirect reference to the various effects of different crops on the soil. The following discussion is not an attempt to consider any or all of these effects in detail but rather it is an effort to produce evidence that may show a relationship between "good" cropping practices and long term soil productivity.

Several agronomists have held that the common fallow-grain sequence of the drier areas of the Great Plains is wasteful of soil fertility (7, 15, 23, 25, 45, 73). Brown (7) reported in 1942 that he collected and analyzed over 1,000 samples of the top six inches of soil from various points in Manitoba, Saskatchewan and Alberta. A summary of nitrogen, organic matter and phosphorus losses as recorded by Brown, is presented in Table 6.

Table 6. Nutrient Losses Resulting From the Cultivation of Six Soil Types in Western Canada

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Nitrogen</th>
<th>Organic Matter</th>
<th>Phosphorus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown</td>
<td>17%</td>
<td>24%</td>
<td>100 lbs.(7%)</td>
</tr>
<tr>
<td>Dark Brown</td>
<td>18%</td>
<td>22%</td>
<td>163 lbs.(11%)</td>
</tr>
<tr>
<td>Black</td>
<td>18%</td>
<td>21%</td>
<td>103 lbs.(5%)</td>
</tr>
<tr>
<td>Black transition</td>
<td>22%</td>
<td>27%</td>
<td></td>
</tr>
<tr>
<td>Gray transition</td>
<td>18%</td>
<td>25%</td>
<td></td>
</tr>
<tr>
<td>Gray</td>
<td>22%</td>
<td>29%</td>
<td>101 lbs.(7%)</td>
</tr>
</tbody>
</table>

In the opinion of the author Brown believed that the most significant finding of his work has been the large losses of organic matter from western Canadian soils. Although organic matter serves as a plant food it also improves the physical condition of the soil and increases its water-holding capacity. Fibrous organic matter is also an important factor in controlling soil erosion by wind and water. Brown concluded as follows:

- 31 -
"If in 30 years we have lost one-fifth to one-third of the organic matter from our soils, very soon we must start replacing or at least maintaining it, possibly by grass or legume rotation. By including such crops as grass or legumes in a rotation, the organic matter can be replaced to some extent and the physical condition of the soil can be improved."

Poyser's (59) findings from Manitoba soils supported this contention. He found that during a 25-year period a cropped soil showed a decrease of 27.9 per cent in organic carbon and 15.9 per cent in nitrogen. When comparing two cropping systems he observed that the organic carbon and nitrogen levels were significantly higher in soils treated with barnyard manure and sweet clover green manure than in soils under a bare fallow treatment. Similar findings have also been reported by Uhland (86).

Obviously wind and water erosion, caused by poor cropping practices, has played a great part in soil depletion (7). From fields under different cropping systems, Uhland (86) has shown how the yields of corn in Indiana were affected by loss of top soil through erosion. His findings appear in Table 7.

Table 7. The Effect of Top Soil Loss on Corn Yields in Indiana

<table>
<thead>
<tr>
<th>Depth of Top soil in inches</th>
<th>Corn Yield per acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>19.8</td>
</tr>
<tr>
<td>1 - 2</td>
<td>30.0</td>
</tr>
<tr>
<td>3 - 4</td>
<td>39.2</td>
</tr>
<tr>
<td>5 - 6</td>
<td>47.0</td>
</tr>
<tr>
<td>7 - 8</td>
<td>53.1</td>
</tr>
<tr>
<td>9 - 10</td>
<td>56.8</td>
</tr>
<tr>
<td>11 - 12</td>
<td>62.4</td>
</tr>
<tr>
<td>12+</td>
<td>69.5</td>
</tr>
</tbody>
</table>

Results similar to those of Uhland were also obtained from similar studies in Ohio, Missouri and Iowa.

It is known that sod crops are essential for effective soil erosion control. Uhland stated that,
"Much of the benefit from growing sod crops is due to the influence they have upon aggregation, or the binding together of soil particles. A high degree of aggregation permits rapid movement of water and air within the soil and consequently prevents excessive runoff."

He reported that on a silt loam soil where alfalfa and bluegrass had grown, soil aggregates were 50 and 58 per cent greater respectively, than on plots in which corn had been grown annually. Uhland also reported on an experiment that showed the effects of different cropping systems on the stability of soil aggregates. In this test, counts were made of the number of drops of water falling 30 centimeters required to disperse an aggregate about the size of a BB shot and wash it through a 20 mesh screen. His findings are presented in Table 8.

Table 8. Average Number of Water Drops Required to Disperse Aggregates of Soil Exposed to Seven Different Cropping Sequences

<table>
<thead>
<tr>
<th>Cropping Sequence</th>
<th>Ave. number of drops required to disperse aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn annually</td>
<td>6.2</td>
</tr>
<tr>
<td>First-year meadow</td>
<td>37.7</td>
</tr>
<tr>
<td>Corn after meadow</td>
<td>10.1</td>
</tr>
<tr>
<td>Second-year meadow</td>
<td>41.2</td>
</tr>
<tr>
<td>Alfalfa 13 years</td>
<td>40.2</td>
</tr>
<tr>
<td>Bluegrass 13 years</td>
<td>31.2</td>
</tr>
<tr>
<td>Clean fallow 13 years</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Uhland concluded by stating that,

"All over the country one can observe the superior physical condition of soils under sods. Where sod has been turned under for corn, more rapid infiltration and less runoff and erosion occur. Also microbial activity and aeration are greater than where corn has been grown annually."
Toogood and Lynch (86) of Alberta found marked soil aggregate differences resulting from cropping practices but few, if any, due to fertilizers. These authors found that soils from a five year rotation of grain and legumes had a mean weight diameter almost double that of soils from plots in a wheat-fallow sequence.

From a long term comparative rotation study on the famous Morrow plots in Illinois, Stauffer, as reported by Wolfe and Kipps (88) summarized the following advantages that a corn, oats, clover rotation that received manure, lime and phosphate had over a continuous corn plot:

(a) The soil on the corn plot has become too acid to grow red clover. Its pH was only 4.8, while the pH of the rotation plot was 6.2.
(b) The organic matter content of the continuous corn plot was down to 3% as compared with 6% in the rotation plot. The top 6 inches of the rotation plot had 30 tons more organic matter per acre than the top 6 inches of the corn plot.
(c) The soil in the corn plot was more compact and less porous than was the case in the rotation plot. The top 6 inches of the corn plot soil weighed 100 tons an acre more than the top 6 inches of the rotation plot. There was much less open space in the soil on the corn plot, for a cubic foot of its soil weighed 85 pounds, and that from the rotation plot only 75 pounds.
(d) On the rotation plots the desirable aggregates - clusters or crumbs of soil - larger than about 1/250 inch in diameter made up almost half (47%) the weight of the soil. Only a third (32%) of the soil on the corn plot was in aggregates of this size.
(e) The rotation plot soil can hold much more water, a quantity equal to 76% of its own weight, while that of the corn plot can hold only 56% of its weight.
(f) Yields have been several times as high on the rotation plot. Part of this higher yield is no doubt due to there being more plant nutrients in the treated plots, but good physical condition must also be credited for a large share.
Chapter 6

Weed Control Through Crop Rotations

One truth long known to agronomists is that the cropping system employed on a farm influences the species and numbers of weeds that will be found. Leighty (45) was so persuaded about the dominating influence of crop rotations on weeds that he made the following statement in 'Soils and Men', the 1938 U. S. D. A. Yearbook of Agriculture.

"Rotation of crops, when accompanied by care in the use of pure seed, is the most effective means yet devised for keeping land free of weeds. No other method of weed control, mechanical, chemical, or biological, is so economical or so easily practiced as a well-arranged sequence of tillage and cropping."

This writer states further that weed problems are likely to be least severe on farms where crop diversification is practiced and most severe on farms devoted for one reason or another to a single crop.

The fact that weeds present a major problem under continuous cropping as well as in cereal crop sequences is reported by many crop rotation workers (1, 7, 12, 15, 19, 25, 26, 32, 40, 45, 47, 54, 60, 75). Even in the early years of the continuous wheat plots on Broadbalk field at Rothamsted, the weed problem was recognized as the chief practical difficulty of continuous cropping (57). Moomaw of North Dakota, noted a decided reduction in yield of grain when cropped continuously, but found this yield decrease to be due to an increase in weeds rather than to a decrease in fertility.

The weed most often referred to as presenting a real problem in dryland grain, fallow sequences is the wild oat. After summarizing studies on cropping systems conducted in Western Canada, Foster (25) concluded that wild oats "now constitutes a very serious threat to crop production on land which has been in summerfallow, wheat, wheat rotation for 20 years." He also points out that, "in the six-year rotations seeded down to grass and alfalfa for two years, very few wild oats are to be found after the same period of cropping." From
an actual experiment at the Brandon Experimental Farm, a similar observation was made in 1946 (60). For some years the agronomists there had observed an increased infestation of wild oats, especially in fields in exclusive grain rotations. The per cent of wild oats by weight, in threshed grain from several different rotations is presented below:

Fallow, wheat (2.6), wheat (13.0), oats (9.0) (manured).
Fallow, wheat (1.8), wheat (15.0), oats (2.6).
Corn, wheat (0.3), hay, hay, wheat (0), oats (0) (manured)
Fallow, wheat (0), hay, hay, wheat (0.2), oats (0.2).
Fallow, wheat (0), hay, oats (0.5).
Hay, wheat (1.1), oats (1.2).
Fallow, wheat (6.0), oats (2.0).

These findings demonstrate the extreme susceptibility of a fallow, grain sequence to infestation by wild oats. Even one year hay in a rotation is shown to reduce wild oat counts substantially.

Another means by which a cropping system may help to control weeds is by including an intertilled crop in the rotation (19, 32, 45, 75). Dubetz (19) evaluated seven different crops as preceding crops in a sequence study and found that plots which had previously grown canning peas were the most weedy and those which had been intertilled with sugar beets, corn and beans had the lightest weed infestations. Seischab (78) also found intertilled crops effective for wild oats control. When following a three-year grain sequence he noted that his barley fields has become polluted with wild oats, but by changing to a cereal, root, root, fodder, cereal sequence, wild oats were effectively controlled. Harrison (32 combined the weed control effectiveness of forages and intertilled crops in what he called a "Cleaning Rotation". This consisted of: summerfallow, corn, barley seeded down, hay, pasture, summerfallow, wheat, wheat. He noted that the first six crops of this rotation helped to clean out wild oats.

Leightly (45) was so convinced about the general effectiveness of crop rotations for weed control that his further comments on this topic bear reproduction. He claimed that,
"Of about 1200 species of plants commonly called weeds in the United States, less than 30 are sufficiently aggressive to be able to survive indefinitely on crop-rotated land. These are the superweeds, the so-called noxious species, plants having such extreme tenacity of life that no ordinary good farming measures control them. They include such notorious pests as Canada thistle, quackgrass, bindweed or wild morning-glory, Johnson grass, hoary cress, nutgrass, leafy spurge and wild onion. All of these are perennials, with spreading or creeping root systems or with underground parts, such as bulbs, uninjured by tillage. A few annuals, notably wild oats and crabgrass, are so resistant to extermination that they may be classed as noxious.

Among the common crops, alfalfa is the one best suited to compete with noxious weeds. The frequent cutting and heavy growth of alfalfa prevent weeds from going to seed and reduce their vegetative vigor. The weeds may not be killed by the alfalfa, but they are usually subdued sufficiently so that other crops can be grown for several years without too much interference. On severely infested land the weeds should be weakened by a month or two of fallow before alfalfa is planted.

The list of other good competitive crops is limited. Winter rye and winter wheat are often recommended for bindweed land because they provide intervals in mid-summer for fallowing and make their own growth during the season when the weed is inactive. Sorghum, soybeans, and Sudan grass have been successful on infested land, although pretillage, especially in the drier areas, is often required for best results and pays well in increased yield of the crops."
Chapter 7

Plant Disease Control Through Crop Rotations

The father of the concept of plant disease control through crop rotations is undoubtedly the famous Dr. Henry L. Bolly, founder of Plot 30 at the North Dakota Agricultural Experiment Station. Coons (14) records that in 1900 Bolly discovered that flax wilt, the most serious of all flax diseases, was caused by a soil infesting fungus, *Fusarium lini*. Bolly added a new concept to plant pathology, namely, that of flax-sick soil - that is, soil infested with *Fusarium lini*. Bolly projected this concept of disease infested soil to apply equally to other crops and other diseases. He demonstrated that the constantly decreasing yields of flax seed in the United States, and the so-called "running out of soil", had a biological explanation. The full significance of Bolly's finding was soon grasped, and the control of soil borne plant parasites by the rotation of crops was quickly adopted.

By today, the use of crop rotations for the control of plant disease has become a common recommendation (13, 16, 18, 20, 30, 45, 47, 48, 56, 73, 88). Leighty (45), writing in "Soils and Men", suggested that certain parasites remain in the soil from season to season, living on plant refuse, and when susceptible crops are grown continuously, the parasites tend to accumulate to a point which makes production unprofitable. It is for this group of parasites that the rotation of crops has proved to be a most effective control measure. Most authors emphasize, however, that crop rotations can be efficient as a means of controlling certain plant diseases, only if clean seed is used, and other field sanitation measures are observed.

At Rothamsted, Glynne (30) compared the infection of wheat straws with eyespot, *Cercospora herpotrichoides*, when wheat followed (a) cultivated land, (b) cut grass, (c) grazed ley and (d) alfalfa. At one location, eyespot infection was 43%, 5%, 1% and 7% for each field in rotation, respectively; at another location 72%, 7%, 6% and 16% respectively. In still another test the yield of wheat
following wheat was 20.5 cwt. per acre as compared with 51 cwt. when following potatoes. In the latter case yield differences were related to a higher incidence of two diseases, eyespot and take-all *Ophiobolus graminis*, as well as to a greater infestation of weeds in the crop following wheat.

Variable disease control effectiveness of different crops in a rotation was observed by Deems and Young (16). These authors made qualitative and quantitative assays of the mycofloras of soils on which alfalfa, oats, corn, sugar beets and grass mixtures were grown following two successive years of sugar beets. A significant reduction of the organism *Aphanomyces cochlioides*, causing black root in sugar beets, was observed only in fields planted to corn and oats. On the other hand, Leighty (45) pointed out that the brown root rot of tobacco in northern areas (the cause of which is uncertain), is unique in that it is controlled most effectively in fields with continuous tobacco culture. Corn and other grasses in the rotation have increased the difficulties of eradicating the disease. Leighty also noted that a seedling damping-off disease of alfalfa caused by *Pythium* spp. increased in a fallowed soil.

Crop rotations may also influence the development of a range of diseases related to the fertility level of a soil. In the U. S. D. A. Yearbook of Agriculture, Plant Diseases, McNew (48) wrote that the state of fertility in a soil determines the prevalence and severity of some plant diseases. For example, if wheat on a moderately fertile soil is given an extra supply of nitrogen it probably will

1. escape seedling diseases more readily,
2. be more subject to pythium root-rot,
3. suffer less from take-all disease, and,
4. be more subject to infection by leaf rust and powdery mildew.

The author points out, however, that higher levels of phosphorus and potassium would have an entirely different effect on those same diseases.

Several other diseases are mentioned as being strongly influenced by different levels of soil nitrogen, phosphorus, potash, calcium and other minerals. Soil pH level, as influenced by crop sequence, may also effect plant
diseases (2, 56). On the slightly acid soils of Rhode Island, Odland (56) found that mangels following mangels in a sequence yielded as low as 0.71 tons per acre compared with an average mangel yield of about 16 tons. The cause for this yield depression was traced to a root-rot organism which found an optimum environment in the soil in which mangels had grown the previous year. Mangels are known to deteriorate the physical condition of the soil in which they grow and to increase the soil acidity and soluble aluminium content. Later, it was found that additions of chloropicrin partially sterilized the soil and prevented the root-rot condition on mangels and other crops. McNew mentioned potato scab as an example of a disease preferring a neutral or alkaline soil (48). Club-root of cabbage and some wilt diseases are known to thrive under acid conditions and may be suppressed by alkaline soils. Concerning the influence of soil organic matter on plant diseases McNew wrote,

"Many plant parasites increase and are disseminated on organic matter, such as plant refuse, manures, and compost. The addition of organic matter to soil, however, often suppresses pathogens if they are poor soil invaders. The organic matter stimulates growth of soil saprophytes that deprive the less aggressive pathogens of mineral nutrients or else they secrete toxic antibiotics. Only a few disease agents are affected appreciably in this way."

Recent advances in the development of disease resistant varieties, nematicides and fungicides have reduced the relative importance of crop rotations as a means of controlling diseases. Nevertheless crop rotations are still useful in controlling diseases caused by fungi and bacteria that cannot long survive in the soil in the absence of their host plants. The following examples of such diseases were listed by Clark (13): bean blight, anthracnose of beans, tobacco root-knot, black shank, and Fusarium wilt, the nematode root diseases of many plants, a miscellany of other soil borne diseases on vegetables including black rot of carrot, Phoma rot of celery, black leg of crucifers, Fusarium wilt of watermelons, fusarium basal rot of onions, Fusarium root rot of peas and beans and Verticillium wilt of strawberries.
Clark also emphasized that not all pathogenic organisms that can grow in the soil can be controlled by crop rotation. As examples he mentioned the fungi causing damping-off, vascular wilts and potato scab. Other organisms cannot grow in the soil in the absence of their host roots, but can persist in the soil almost indefinitely because of their ability to form dormant resting bodies like spores, or like the sclerotia in Sclerotinia wilt of sunflowers.

In the Canada Department of Agriculture publication, Diseases of Field Crops in the Prairie Provinces (18), nearly ninety diseases that attack the field crops of Western Canada are discussed. Control recommendations for nearly one-third of these call for the rotation of crops to either reduce or eliminate the causal organism, and thus the disease. A summary of western Canadian field crop diseases for which crop rotation is a recommended measure of control follows:

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Casual organism(s)</th>
<th>Crops Attacked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common root-rot</td>
<td>Helminthosporium sativum</td>
<td>wheat, barley, grasses</td>
</tr>
<tr>
<td></td>
<td>Fusarium spp.</td>
<td></td>
</tr>
<tr>
<td>Ergot</td>
<td>Claviceps purpurea</td>
<td>wheat, rye, grasses</td>
</tr>
<tr>
<td>Bacterial blights</td>
<td>Xanthomonas translucens</td>
<td>wheat, barley, grasses, rye</td>
</tr>
<tr>
<td></td>
<td>Pseudomonas atrofaciens</td>
<td></td>
</tr>
<tr>
<td>Speckled leaf disease</td>
<td>Septoria avenae f. sp triticea</td>
<td>wheat</td>
</tr>
<tr>
<td>Spot blotch</td>
<td>Helminthosporium setivim</td>
<td>barley</td>
</tr>
<tr>
<td>Net blotch</td>
<td>Helminthosporium teres</td>
<td>barley</td>
</tr>
<tr>
<td>Speckled leaf blotch</td>
<td>Septoria passerinii</td>
<td>barley</td>
</tr>
<tr>
<td>Scald</td>
<td>Rhynchosporium secales</td>
<td>barley</td>
</tr>
<tr>
<td>Flax rust</td>
<td>Melampora lini</td>
<td>flax</td>
</tr>
<tr>
<td>Asco</td>
<td>Septoria linicola</td>
<td>flax</td>
</tr>
<tr>
<td>Seedling blight</td>
<td>Rhizoctonia solani</td>
<td>flax, alfalfa</td>
</tr>
<tr>
<td>And root rot</td>
<td>Pythium spp. Fusarium spp.</td>
<td></td>
</tr>
<tr>
<td>Flax wilt</td>
<td>Fusarium oxysporum f. lini</td>
<td>flax</td>
</tr>
<tr>
<td>Stem break and browning</td>
<td>Polyspora lini</td>
<td>flax</td>
</tr>
<tr>
<td>Unflower rust</td>
<td>Puccinia helianthus</td>
<td>sunflower</td>
</tr>
<tr>
<td>Sclerotinia wilt</td>
<td>Sclerotinia sclerotiorum</td>
<td>peas</td>
</tr>
<tr>
<td>Disease</td>
<td>Cause</td>
<td>Host</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Aschochyta blight</td>
<td><em>Aschochyta pisi</em>, <em>A. pinodeLLA</em></td>
<td>peas</td>
</tr>
<tr>
<td>Root rot</td>
<td><em>Mycosphaerella pinodes</em></td>
<td>peas</td>
</tr>
<tr>
<td></td>
<td><em>Fusarium solani</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Pythium ultimum</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Aphanomyces eutiches</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Zhizochtonia solani</em></td>
<td></td>
</tr>
<tr>
<td>Bacterial wilt</td>
<td><em>Corynebacterium insidiosum</em></td>
<td>alfalfa</td>
</tr>
<tr>
<td>Winter crown rot or snow mould</td>
<td>unidentified basidiomycete</td>
<td>alfalfa</td>
</tr>
<tr>
<td>Crown or root diseases of alfalfa</td>
<td>various soil borne fungi</td>
<td>alfalfa</td>
</tr>
<tr>
<td>Stem nematode of alfalfa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crown and root rot</td>
<td>various soil borne fungi</td>
<td>clover</td>
</tr>
<tr>
<td>Septoria leaf spots</td>
<td><em>Septoria</em> spp.</td>
<td>grasses</td>
</tr>
</tbody>
</table>

- 42 -
Chapter 8

Insect Control Through Crop Rotations

Rotation of crops often helps to reduce insect injury, particularly by insects of restricted feeding habits (2, 24, 50, 53, 80). Insects may be classified into three groups according to their feeding habits. Monophagous species can survive on only one, or very few plant species; the oligophagous group is limited to species within only one plant family, e.g. the cruciferae, and thus attack a somewhat wider range of host plants than the monophagous group; the polyphagous type of insects are general feeders and may survive on the tissues of a wide range of plants. However, among insects that injure cultivated crops the number of general feeders is very small. Species feeding on the plants of one family are fairly numerous, but most insects feed on only a few very closely related species (50). Metcalfe and Flint (50) list 26 insects that attack corn, 20 that damage wheat and 15 that may harm red clover. It is interesting to note from these lists that eight of the insects that are listed as pests of corn are also listed as pests of wheat, but that only three of the 61 insects are serious pests of all three crops (grasshoppers, armyworm, variegated cutworm). The authors then comment as follows on the significance of this observation to crop rotations.

"Wheat and corn are grasses, clover is a legume; and it will be seen from a study of these lists that much can be accomplished in preventing insects from becoming seriously abundant in our fields, if a good rotation is practiced where a crop of one plant family follows that of a different family...A large part of the increased yields obtained from a rotation where grains follow legumes, and legumes grains, is due to the reduction in insect damage. Crops of the same group, such as corn, oats and wheat, grown on the same land, year after year, give a condition favorable to the insects that attack the grass crops; and the same is true of a number of years cropping of ground with plants of any one family."

These workers further point out that in order for insects to
be effectively controlled by the rotation of crops they must have limited powers of migration or sluggish habits and be slow breeders and spend a relatively long time in the feeding stage, besides having a very limited host range. Because of these limitations the rotation of crops can effectively "starve out" and so control only a limited number of injurious crop insects.

A brief consideration of the influence of crop rotation on individual insect pests now follows. Denwick (17) of Rothemsted found that the greatest build-up of eel-worm *Heterodera major* on experimental grain plots occurred under oats, remained constant under barley and decreased under rye. Fleming (18), writing in "Soil", stated that a crop sequence of wheat, wheat favors an increase in infestation by the hessian fly, the false wireworm, the winter grain mite, the wheat jointworm, the wheat stem sawfly, and the wheat strawworm. He then suggested the following crop sequence changes that could control each of these insects. The hessian fly might be controlled by breaking the wheat sequence with oats, buckwheat, corn or sorghum.

"Legumes or sorghum are recommended to break the cycle for the false wireworm; corn sorghum or clover for the winter grain mite; rye, barley, oats or buckwheat for the wheat jointworm; and barley, oats, corn, flax or mustard for the wheat stem sawfly. Since wheat is the only host of the wheat strawworm any other crop will break its cycle."

The author also found that Chinch bugs could be controlled by planting a legume or some other immune crop into a sequence or corn, wheat, barley, oats or rye. A rotation avoiding successive crops of corn on the same land would do much to control the corn root aphid, the seed-corn maggot, the northern corn rootworm, the southern cornstalk borer, and the sugar-cane beetle. Damage from the European corn borer could be reduced by following a four-year rotation of corn, soybeans, small grain and clover.

In the booklet, *Field Crop Insects and Their Control in the Prairie Provinces*, Mitchener (53) described in considerable detail twenty-two of the most destructive crop insects in Western Canada (besides mentioning many more), and
suggested crop rotation as an effective control measure for the following eight of these insects.

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Scientific Name</th>
<th>Susceptible Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Banded sunflower moth</td>
<td>Phalonia lopes</td>
<td>sunflower</td>
</tr>
<tr>
<td>Sunflower moth</td>
<td>Homeosoma electellum</td>
<td>sunflower</td>
</tr>
<tr>
<td>European corn borer</td>
<td>Pyrausta nubilatus</td>
<td>corn</td>
</tr>
<tr>
<td>Sweet clover weevil</td>
<td>Sitona cylindricollis</td>
<td>sweet clover</td>
</tr>
<tr>
<td>Prairie grain wireworms</td>
<td>Ctenicera aeripennis</td>
<td></td>
</tr>
<tr>
<td>Wheat stem sawfly</td>
<td>Cephus cinctus</td>
<td>wheat, spring</td>
</tr>
<tr>
<td>Wheat stem maggot</td>
<td>Meromyza americana</td>
<td>wheat</td>
</tr>
<tr>
<td>Hessian fly</td>
<td>Phytophaga destructor</td>
<td>wheat, barley</td>
</tr>
</tbody>
</table>

* Wheat, spring rye, corn, potato and sunflower are more susceptible to larval injury than oats, barley, sweet clover and alfalfa.
Chapter 9

Effects of Crop Rotation on Crop Quality

Crop rotation not only tends to increase per acre production but as a rule also insures better crop quality than continuous cropping. With certain crops some workers experienced difficulty in assessing rotation effect on crop quality, but nevertheless agreed that the beneficial effects of rotations on weed, disease and insect control warranted a general conclusion that crop rotation improves crop quality (45, 87).

Several investigators have found that a direct relationship exists between the quality of wheat, the most important crop of the Great Plains area, and the crop rotation employed (10, 23, 36, 45, 87, 89). After three years' testing, Ellis (23) of Manitoba, obtained an average protein content of 15.32 per cent from wheat as second crop after alfalfa compared with 12.56 per cent from wheat as second crop after grasses. Champlin and Wall (10) of Saskatchewan obtained the following protein contents from Marquis wheat when seeded in eight different rotations over a twenty-year period:

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Per cent protein</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Continuous wheat</td>
<td>14.3</td>
</tr>
<tr>
<td>(b) Fallow wheat</td>
<td>15.1</td>
</tr>
<tr>
<td>(c) Corn in hills, wheat</td>
<td>14.9</td>
</tr>
<tr>
<td>(d) Oats in rows, wheat</td>
<td>14.3</td>
</tr>
<tr>
<td>(e) Fallow, wheat, sweet clover</td>
<td>15.5</td>
</tr>
<tr>
<td>(f) Corn in hills, wheat, sweet clover</td>
<td>15.5</td>
</tr>
<tr>
<td>(g) Oats in rows, wheat, sweet clover</td>
<td>15.6</td>
</tr>
<tr>
<td>(h) Fallow, wheat, oats in rows, wheat, alfalfa, alfalfa</td>
<td>16.4</td>
</tr>
<tr>
<td>(i) Fallow, wheat, oats in rows, wheat, bromegrass, bromegrass</td>
<td>15.7</td>
</tr>
<tr>
<td>(j) Fallow, wheat, oats in rows, wheat, alfalfa, alfalfa</td>
<td>15.6</td>
</tr>
</tbody>
</table>
(k) Fallow, wheat, oats in rows, 
wheat, bromegrass, bromegrass 15.0

By introducing sweet clover into rotations (e), (f) and (g) the average per cent protein of wheat increased by 0.4 on fallow, 0.6 on corn land and 1.3 following oats in rows, as compared to the average obtained in rotations (b), (c) and (d). In rotation (h), wheat on fallow after alfalfa had an average protein content of 16.4 per cent as compared to 15.7 per cent on fallow after brome in rotation (i). The second crop of wheat in this rotation, grown four years after alfalfa, yielded 15.6 per cent protein compared with 15 per cent four years after brome. Thus, it appears that under Saskatchewan conditions, legumes in a rotation may influence protein content of wheat, even up to four years after the legume appeared in the sequence. Wolfe and Kipps (89) reported that corn grown in the four-year rotation - corn, wheat, hay, hay (mammoth clover, timothy, redtop) produced 75.22 per cent marketable corn compared with 54.66 per cent from continuous corn. Similarly, workers in Nebraska concluded that the use of forage legumes and manure both tended to increase the protein content of corn, wheat and oats (42). From personal communications with Meredith (51), it was learned that where wheat protein content is materially increased by a legume rotation, the quality of malting barley would likely be proportionally impaired because of a higher nitrogen content. Similarly, an increased soil nitrogen content would tend to increase the nitrogenous content of sugar beets at the expense of sucrose content. From a twenty-two year study Larson (44) of Montana noticed that sugar beets grown (under irrigation) in rotations not including alfalfa contained an average of 17.2 per cent sucrose whereas sugar beets from rotations including alfalfa contained 16.1 per cent sucrose. In addition, the alfalfa rotation increased the percentage of sugar beet tops from 32 to 43 per cent although the root weight in the legume rotation averaged .18 pounds compared to 0.87 pounds in the non-legume rotation. It appears that this legume-protein relationship may be limited to areas where moisture is a limiting factor. Russell observed that when water supplies are limited, plants take less vegetative growth and thus use less of the available nitrogen for vegetative growth. This excess of available nitrogen is then translocated to the grain and produces a
higher protein content (87).

Crop quality should be of particular concern to a mixed farm operator who produces feed for livestock. To such a farmer a realistic evaluation of a crop rotation would take into serious account the total nutritive units produced. Crop rotation studies in which the nutritive units produced by the various sequences were evaluated were conducted by Uhland (86) and by Chen and Arny (11). Uhland compared five rotations on the basis of pounds of total digestible proteins and total digestible nutrients per acre. Below is an example of his method of evaluating this fifteen year experiment.

<table>
<thead>
<tr>
<th>Crop Rotation</th>
<th>Total Digestible Proteins</th>
<th>Total Digestible Nutrients</th>
</tr>
</thead>
<tbody>
<tr>
<td>corn continuous</td>
<td>108</td>
<td>1,215</td>
</tr>
<tr>
<td>corn, wheat</td>
<td>237</td>
<td>2,250</td>
</tr>
<tr>
<td>corn, wheat, alfalfa</td>
<td>382</td>
<td>2,710</td>
</tr>
<tr>
<td>corn, wheat, alfalfa, alfalfa</td>
<td>520</td>
<td>3,092</td>
</tr>
<tr>
<td>corn, oats, alfalfa, alfalfa, alfalfa</td>
<td>533</td>
<td>3,055</td>
</tr>
</tbody>
</table>

The four and five year rotations produced five times the amount of digestible protein and more than twice as great an amount of digestible nutrients as continuous cropping to corn.

In addition to the effect on grain protein and total digestible proteins, the rotation of crops has also been observed to influence the production of plumper grain kernels with a higher weight per bushel than is produced from continuous cropping (45, 89).

Rather surprising is the fact that the crop rotation literature is relatively barren of references to crop quality, as affected by rotation. As much of the produce from our fields faces an ever more competitive foreign market, aspects of crop quality will constantly become more important.
PART THREE

ROP ROTATION STUDIES IN WESTERN CANADA

Chapter 10

A Historical Review

In the 1880's western Canadian agriculture lost much of its heretofore good reputation and allure, for agriculture in the west was in serious difficulty and its future was uncertain. During the decade of the 1880's as many as five crops resulted in total or near failure because of drought and early frost. Many settlers were disillusioned and left the country. However, in 1885-1886 an important and far reaching event in Canadian history took place on the Bell Farm at Indian Head. In 1885 General Middleton conscripted the horses from the Bell Farm for active service in the Nor'west Rebellion and did not return them until June the following year. As June was too late for seeding, the land lay "fallow" for the entire summer but was seeded again the following spring. The next year, 1886 was a drought year and crops grown on stubble were almost a total failure. But the Bell "fallow" field produced a good crop. Reports of this good crop in a dry year attracted much attention throughout the Great Plains area and gave new hope to farmers in the Canadian west. Thus, in the first annual report of the Indian Head Experimental Farm in 1889, Superintendent Angus Mackay wrote as follows:

"Our season points to only one way in which we can in all years expect to reap something. It is quite within the bounds of probabilities that some other and perhaps more successful method may be found, but at present I submit that fallowing the land is the best preparation to insure a crop" (83).

The Canadian historian, A. S. Morton (55), notes in his "History of Prairie Settlement" that the discovery of summerfallow was a great boon to the economic development of the prairie because it greatly reduced the risk hazard of crop production. However, all the problems of cropping in the west had not been solved by the discovery of summerfallow.
The climate barrier break-through to a reliable and prosperous agricultural economy was by no means complete, nor is it complete today. It was obvious that much experimental work was needed to determine the limitations, and the most efficient use of summerfallow, and other farm practices.

Much credit is due the early statesmen of this nation who had foresight enough in 1886 to pass the Act of Parliament that authorized the establishment of a "Central Experimental Farm and Four Branch Farms" (31). Of the four branch farms originally established, the two that had, perhaps, the greatest impact on Western Canadian agriculture were established in 1888 at Indian Head and at Brandon.

Although Angus Mackay was aware of the need for moisture conservation practices on western farms when he arrived at Indian Head in 1888, the first crop rotation plots were not established until eleven years later, in 1899. These first systems of rotation were to,

"keep up fertility, prevent the land becoming overrun with weeds, afford a comparison between the value of summerfallow and the plowing under of leguminous crops and, at the same time, by giving the farmer a wider range of products, afford him a better opportunity of having at least one good crop in almost any year" (31).

A few historical references to the early days of crop rotation studies at the Brandon Experimental Farm were made on Page 4. These early rotation experiments at Indian Head and Brandon continued only until about 1909 when a new, more comprehensive set of experiments were being planned for the Experimental Farms of Western Canada.

With the establishment of this new series of comparative rotation experiments at Brandon, Indian Head, Scott, Rosthern, Lacombe and Lethbridge in 1910 and 1911, a new era in crop rotation studies got under way on the Canadian prairies. Certainly a variety of crop sequences were compared at a number of locations. In order to facilitate the comparison of the same rotations at a number of stations, each rotation established was designated with a letter of the alphabet.

- 50 -
To illustrate the extensiveness of this new project, the crop sequences of all rotations established from 1910 to 1912 are listed below (31).

<table>
<thead>
<tr>
<th>Rotation</th>
<th>Crop Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Wheat continuously.</td>
</tr>
<tr>
<td>B 2 year</td>
<td>Summerfallow (S.F.), wheat.</td>
</tr>
<tr>
<td>C 3 year</td>
<td>S.F., wheat, wheat or coarse grain.</td>
</tr>
<tr>
<td>D 4 year</td>
<td>Wheat (manure in fall), wheat, oats, S.F.</td>
</tr>
<tr>
<td>E 4 year</td>
<td>Wheat, wheat, oats, S.F.</td>
</tr>
<tr>
<td>F 5 year</td>
<td>Wheat, wheat (manure in fall), corn or root, oats and barley (seeded down with grass and clover), clover hay.</td>
</tr>
<tr>
<td>G 6 year</td>
<td>Wheat, wheat, oats and barley (seeded with grass and clover), clover hay, pasture (manure in fall), corn or roots.</td>
</tr>
<tr>
<td>H 6 year</td>
<td>Wheat, wheat, S.F., oats (seeded with grass and clover), clover hay, pasture (manure in fall).</td>
</tr>
<tr>
<td>I 6 year</td>
<td>Flax, oats, S.F., wheat (seeded with grass and clover), clover hay, pasture (manure in fall).</td>
</tr>
<tr>
<td>J 6 year</td>
<td>S.F., wheat, wheat or coarse grain, oats (seeded with rye grass, red clover and alfalfa), hay, pasture.</td>
</tr>
<tr>
<td>K 6 year</td>
<td>Hoed crop, wheat, barley (seeded down), hay (12 ton manure), pasture, pasture.</td>
</tr>
<tr>
<td>L 6 year</td>
<td>Hay, pasture (12 ton manure), pasture, wheat, oats, barley (seeded to timothy, alsike and red clover).</td>
</tr>
<tr>
<td>M 6 year</td>
<td>S.F., wheat, coarse grain (manure in fall), S.F., peas and oats for hay, barley or oats.</td>
</tr>
<tr>
<td>N 7 year</td>
<td>Alfalfa, alfalfa (6 ton manure) alfalfa, wheat, grain.</td>
</tr>
<tr>
<td>P 8 year</td>
<td>S.F., wheat, wheat, S.F., roots or legume (15 ton manure), barley (seeded to rye grass and red clover), hay, pasture.</td>
</tr>
<tr>
<td>Q 8 year</td>
<td>(For sheep on light hill land). Roots and peas, wheat and oats (seeded to grass and clover), hay, hay, pasture, pasture, green feed rape (manure in fall).</td>
</tr>
<tr>
<td>R 9 year</td>
<td>S.F., hoed crop or legume (15 ton manure), wheat, oats, S.F., wheat, oats (seeded</td>
</tr>
</tbody>
</table>
to rye grass, red clover and alfalfa), hay, pasture.

S 9 year S.F., hoed crop, wheat, S.F., wheat, coarse grain, S.F. (manured), peas and oats for hay (seeded in fall to rye), rye, pasture.

T 10 year S.F., wheat, oats or barley, S.F. in May (seed alfalfa in June), alfalfa, alfalfa, alfalfa, hay or pasture, S.F., hoed crop, wheat (manure on stubble).

U 10 year Seed alfalfa, alfalfa, alfalfa, alfalfa, alfalfa, alfalfa, hoed crop, wheat, wheat or coarse grain, coarse grain.

alfalfa continuously.

V

W 10 year wheat, wheat (manure in fall), corn or roots, oats, barley, alfalfa, alfalfa, alfalfa, alfalfa (plough in mid-summer).

The locations where each of these rotations were established are shown in Figure 1.

The task of appraising and evaluating the findings of an experimental undertaking as extensive as this one and that has produced a mass of data for nearly half a century, is indeed formidable and difficult. Evaluating the Experimental Farm experiments on crop rotations to date would be somewhat less perplexing if one was clear as to the original aims and objectives of these tests. Concise statements of purpose for these rotation studies are difficult to find. For example, the following two rather different objectives were given in the same publication for the rotation studies outlined above: (a) "to obtain data as to the most profitable rotation to adopt, while still maintaining the fertility of the soil" and (b) "the necessity of having to introduce a summerfallow occasionally to create a supply of moisture in the subsoil makes the problem of determining suitable rotations a difficult one. To gather information along this line a number of rotations were inaugurated in the spring of 1911" (31). Judging by the manner in which these studies have been conducted in the field and reported in bulletins the former of the two purposes appears to express the original intent more accurately.
Figure 1. Crop Rotations Established at Six Western Canadian Experimental Stations

<table>
<thead>
<tr>
<th></th>
<th>Indian</th>
<th>Brandon</th>
<th>Head</th>
<th>Rosthern</th>
<th>Scott</th>
<th>Lacombe</th>
<th>Lethbridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>I</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In 1928 Hopkins and Barnes (40) published a progress report on these experiments and presented details as to the yields and profits obtained from the different rotations and some information regarding their suitability for different conditions. The authors made the following statement which might be interpreted as one of the prime purposes of the experiments:

"As this information has been secured over a long period of years, it affords a fairly reliable guide to farmers living in districts served by these farms."

Undoubtedly, findings of these comparative rotation studies
have served as valuable guideposts for farmers who were trying desperately to cope with the climatic extremities and uncertainties so characteristic of dryland agriculture. Although these studies have produced much "good advice" for farmers, it is doubtful whether they have contributed greatly to the stockpile of scientific facts, or principles, that can be applied elsewhere. In the following chapters an attempt will be made to review some of the guideposts mentioned above and to draw attention to some of the limitations inherent in the original layout of these experiments and in the usefulness of the data subsequently accumulated.

General Observations from Crop Rotation Experiments in Western Canada

Most of the findings from past crop rotation experiments in Western Canada could be considered under the following general headings:

(a) Effect on crop rotation of varying degrees of moisture limitation.
(b) Management practices of manures and commercial fertilizers within a rotation.
(c) Effects of different cropping practices on long term soil fertility.
(d) Effect of cropping system on control of weeds, crop diseases and insects.

In the chapters that follow, Part (a) will be discussed in considerable detail, Part (b) in less detail, and only occasional references will be made to parts (c) and (d) as they have been dealt with separately in earlier chapters.
Chapter 11

**Effects of Varying Degrees of Moisture Limitation on Crop Rotations**

Since moisture is the chief limiting climatic factor to grain production in Western Canada, experiments in cropping practices will obviously be concerned with the most efficient utilization of available moisture. For this reason most of the crop rotation workers in the prairie provinces have concentrated on the problem of determining the optimum frequency of summerfallow and the kind and sequence of crops necessary for maximum per acre production and income consistent with good soil and moisture conservation. Findings from such experiments would, of course, differ from area to area depending primarily on annual precipitation, but they would also be influenced by summer temperatures, wind velocities and texture and fertility of soil on which the rotations were compared.

Thus, the data from crop rotation at a particular location should be evaluated only in terms of the climatic conditions under which the data were obtained. Consequently, the long term average annual precipitation data are essential when evaluating any crop rotation findings and conclusions. These data for several western Canadian experimental stations are presented below.

<table>
<thead>
<tr>
<th>Station</th>
<th>No. of Years</th>
<th>Period</th>
<th>Ave. precipitation in inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winnipeg</td>
<td>77</td>
<td>1872-1949</td>
<td>20.49</td>
</tr>
<tr>
<td>Jorden</td>
<td>28</td>
<td>1919-1946</td>
<td>20.09</td>
</tr>
<tr>
<td>Brandon</td>
<td>57</td>
<td>1891-1947</td>
<td>18.16</td>
</tr>
<tr>
<td>Indian Head</td>
<td>43</td>
<td>1903-1946</td>
<td>17.35</td>
</tr>
<tr>
<td>elfort</td>
<td>9</td>
<td>1938-1946</td>
<td>15.10</td>
</tr>
<tr>
<td>hitefox</td>
<td>20</td>
<td>1937-1957</td>
<td>16.10</td>
</tr>
<tr>
<td>Regina</td>
<td>63</td>
<td>1883-1946</td>
<td>14.66</td>
</tr>
<tr>
<td>wift Currentcott</td>
<td>25</td>
<td>1922-1946</td>
<td>13.48</td>
</tr>
<tr>
<td>anyberries</td>
<td>19</td>
<td>1929-1947</td>
<td>11.30</td>
</tr>
<tr>
<td>ethbridge</td>
<td>45</td>
<td>1902-1946</td>
<td>15.84</td>
</tr>
<tr>
<td>acombe</td>
<td>39</td>
<td>1908-1946</td>
<td>17.73</td>
</tr>
<tr>
<td>eaverlodge</td>
<td>32</td>
<td>1916-1947</td>
<td>17.36</td>
</tr>
</tbody>
</table>

(6, 60, 62, 63, 65, 66, 67, 68, 69, 70, 71, 72)
Because of the different number and period of years represented in each average precipitation figure listed, these data are of limited value for comparing long term annual precipitation totals between stations. Nevertheless they indicate a consistent trend of decreasing annual precipitation when moving west from Winnipeg (20.49 inches) to Manyberries (11.30 inches). A gradual increase is again noted from southern Alberta westward to Lacombe (17.73) and the foothills. One should remember, however, that average precipitation figures, like average yield figures, are of little or no value to predict what moisture or yield conditions might be in a given year or period of years.

Extreme year to year variation in climate is the rule in western Canada rather than the exception. For example, the 36 year average precipitation at Scott, Saskatchewan was 13.8 inches. Of these 36 years only nine years were close to the 13.8 inch average; during 10 years the precipitation was considerably below and during 17 years considerably above the 13.8 inch average. The extreme variability is shown in that the all time high during that period was 20.79 inches in 1916, and two years later, in 1918, the all time low precipitation of 6.59 inches was recorded. As moisture is the chief limiting factor to grain production the yields of wheat on fallow followed a similar pattern. Only three seasons produced a yield near the 36 year average of 15.9 bushels per acre. During twenty years the yields were considerably lower and averaged 8.8 bushels. The remaining thirteen years averaged 26.6 bushels per acre. Thus, average data from long term studies of this nature should be considered only as guides when evaluating a cropping program (71).

When examining crop rotation data that has been accumulated across the prairies there emerges a rather obvious relationship between annual precipitation and the length of the most profitable rotation. A number of common dryland cropping sequences will be examined in the following sections.

Although the Experimental Farm Progress Reports and some other publications rely heavily on their interpretation
of "net profit" when comparing rotations, this discussion will not concern itself with many net profit figures because the cost-price relationships on farms when these figures were recorded have no validity today.
Chapter 12

Studies With Continuous Wheat and Fallow, Grain Sequences

Continuous Wheat

Wheat has been grown continuously at Lethbridge, Alberta, and at Scott, Saskatchewan, since 1911. After the first fifteen years of cropping both of these plots had become very weedy. The yields had fluctuated greatly and were closely related to seasonal rainfall (40). However, at Lethbridge, after 35 consecutive years of cropping, weeds were no longer a problem as tillage practices had been found to keep them under control. Furthermore, in the thirty-fifth year, the yield of continuous wheat was better than wheat after wheat in the summerfallow, wheat, wheat, rotation that lay alongside of it. This suggests that the continuous field was as free of weeds and as fertile as the rotation containing fallow. Even so, the continuous wheat did not produce as much wheat per total land area used as did the two and three year fallow, grain sequences (66).

Fallow-Grain Sequences

Long term experiments would indicate that considerations other than just soil moisture must be taken into account when determining the length of summerfallow, grain sequences. In 1928 Hopkins (40) wrote as follows:

"On the various Dominion Experimental Farms where accurate records have been kept for many years, the yields on ploughed stubble land have ranged from approximately 60 per cent to 80 per cent of the yields on summerfallow. In individual years these percentages have varied widely and, of course, certain farms have consistently given different results from farms in other districts. On the whole, however, the yields on stubble land have been sufficiently high to make the three-year rotation more profitable than the two year."

However, in 1954 Foster (25) reported that in the drier grain
growing areas of Western Canada the two-year fallow, grain sequence was gaining in popular use over the three year fallow, grain, grain sequence. He produced data from seven locations between Lethbridge and Indian Head that indicated very little difference in average yields per cultivated acre between the two and three year sequences. Foster attributed the increased popularity of the two year sequence to the widespread use of the combine and the resulting tillage problem caused by heavy straw and stubble residues. By alternate fallow, grain cropping the farmer has adequate trash cover protection for his fallow years, is better able to control perennial weeds and will be able to prepare a good seedbed the following spring. He stated further, however, that in the area east of Indian Head, yield returns favor the three-year rotation slightly, presumably because of a somewhat higher annual precipitation.

Moisture studies in the drier areas have shown that when the soil moisture on a stubble field gets down to a depth of 48 inches in the fall, it is reasonable to expect a fair yield of grain on that field the following year. Thus, the individual grain farmer might shift between a two and three-year rotation if other factors like weeds, straw management or seedbed preparation are not the factors that determine the length of rotation. From all the rotation work done at Brandon, the two-year fallow, wheat sequence has not been found as profitable as longer rotations, provided oats and barley were used as stubble crops instead of wheat (8).

A summary of the wheat yields from a Frequency of Fallow experiment conducted by Professor Ellis at the University of Manitoba for a period of 21 years, indicated that frequent fallowing decreased the average yearly yield per acre (84). The average wheat yields in this test were as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Yield (bushels per acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>continuous wheat</td>
<td>27.25</td>
</tr>
<tr>
<td>fallow, 3 years wheat</td>
<td>22.10</td>
</tr>
<tr>
<td>fallow, 2 years wheat</td>
<td>21.52</td>
</tr>
<tr>
<td>fallow, wheat</td>
<td>18.90</td>
</tr>
</tbody>
</table>

This study was conducted on clay soils near Winnipeg (20.49 inches annual precipitation). Although this long term experiment found that fallowing has no beneficial effect on long
term crop production in the Winnipeg area, it is noteworthy that the yields from the continuous wheat plot decreased to as low as 5 bushels per acre during the dry 1930's, whereas the wheat yields from the rotations including fallow did not vary as much from the 21 year average. The close relationship between the water requirements of grain crops and their optimum arrangement in a crop sequence has been mentioned in Chapter 4, in which reference was made to studies conducted at Swift Current and Brandon.

The disadvantages of fallow-grain rotations have been referred to frequently in other sections of this report. Several authors have mentioned the rapid breakdown of soil fibre and organic matter, the increasing incidence of wild oats and other weeds, certain plant diseases and insects as well as the increased susceptibility of the soil to wind and water erosion, when a short fallow, grain cropping system is followed (15, 25). However, in the drier areas of Canada the moisture conserving aspect of the fallow, grain rotations appears to overbalance these obvious disadvantages. In a paper entitled, "Wheat Yields and Soil Fertility on the Canadian Prairies after a Half Century of Farming", Hill (37) concluded rather optimistically as follows:

"At three Experimental Stations in Western Canada the yields of spring wheat on summerfallow in grain rotations have been maintained for 40 years without the addition of fertilizer or manure. Yields of wheat following wheat in these rotations at two stations may have declined slightly but this was not due entirely to reduced fertility since weed infestations have adversely affected yields.

At the Lethbridge station in Alberta, average losses of 25 per cent nitrogen and 19 per cent organic matter have occurred in the grain rotations since 1910.

It appears that a cropping practice which includes wheat and summerfallow can be continued profitably for some time to come in Western Canada if soil erosion and weeds can be controlled."
Chapter 13

Studies With Fallow, Grain, Forage Rotations

Numerous experiments have been conducted in the western provinces in which different combinations of fallow, grain and forage have been compared. From the standpoint of experimental design the validity of many comparisons so freely drawn from these experiments is open to serious question. Some of these questions will be raised in Part IV. However, the purpose of this review is not primarily to compare and review individual experiments, but rather to attempt to establish general trends that might have application under similar environmental conditions.

As most cultivated forage crops are perennial in life habit and have a very high water requirement in comparison to grain crops (73), the soil moisture available would, to a large extent, determine the practicability of including forage crops in a rotation. Factors other than water requirement that would influence the inclusion of forage crops in a system of cropping would be, (a) the level of soil fertility, (b) the physical condition of the soil and its susceptibility to erosion, (c) the prevalence of weeds, plant diseases and insects, (d) the extent of complementary farm enterprises like livestock, etc., and (e) the desirability of distributing the farm income and farm labor over a broader base.

Although precise complementary and competitive relationships have not yet been established for most soil zones in western Canada, some general trends have been observed. Under the semi-arid conditions prevailing at Regina, Swift Current, Scott and Lethbridge the use of grasses and legumes in rotations has not met with much success, especially when the forage is seeded down a year or two after the summerfallow year. Under these conditions of dryland farming no increases in yields of wheat on summerfallow have been obtained by including grasses and legumes in a rotation. However, forages have, in many instances, afforded wild oat control. Under conditions of drought it frequently takes two or three years to establish a good stand, if, indeed, one can be established at all. However,
once a forage stand is established in semi-arid regions, it should be left down for several years so that a good sod can be formed. Combination rotations that combine a short fallow, grain sequence with a forage field left down for several years have been tried and found to be of some value in reducing the wind erosion hazard of the field and in affecting some weed control (66).

Studies at Indian Head

Experimental results indicate that a complementary relationship between grain and forages in rotations begins to emerge when moving eastward from eastern Saskatchewan. Two classic experiments, one at Indian Head and one at Whitefox, Saskatchewan, clearly indicate a long term beneficial effect of forages on grain yield and net income per acre when comparing a fallow, grain with a fallow, grain, forage rotation. At Indian Head a three-year fallow, wheat, wheat rotation has been compared with a nine-year mixed farming rotation since 1912 (64). The crop sequence in this nin-year rotation is: summerfallow, wheat, oats seeded down to grass-legume mixture, hay, hay, hay and break, corn, wheat, oats. For the first ten years of the experiment (1912-1921), wheat on fallow in the mixed farming rotation averaged 36.1 bushels per acre compared with 28.7 bushels for the three-year rotation. During a recent ten-year period (1947-1956) the yields were 46.8 bushels per acre from the mixed, compared with 28.4 bushels from the grain rotation. The 45-year average yields were 36.1 bushels from the mixed farming and 26.6 bushels from the grain rotation.

Large differences were also evident in the second crop after fallow. During a recent ten-year period in the grain rotation, wheat after wheat averaged 14.7 bushels or 887 pounds of grain. In the 9-year rotation oats after wheat averaged 64.5 bushels per acre of 2,193 pounds of grain. The average weight of grain produced per acre (including the total rotation) from 1947 to 1956 was 862 pounds from the fallow, grain sequence and 1,073 pounds from the 9-year rotation. Besides the extra grain, the 9-year rotation produced about 1 ton of corn and .45 tons of grass-legume hay per acre each year.
In the ten-year period from which the above data were taken, the three years of forage were complementary to the grain in the 9-year rotation because it appears that the forage affected an over-all increase in yield of grain per acre. Because the design of this experiment was rather poorly conceived and the specific purpose was not recorded, the conclusions, if any, must be drawn cautiously. From the layout of the experiment it is impossible to determine the specific cause for the higher per acre production in the mixed grain rotation. Whether the increase in grain yield can be attributed to (a) less frequent summerfallowing (b) corn in the rotation (c) the cropping sequence or (d) the forage crops is not known. All that can be safely concluded is that the mixed farming rotation, as a unit, was more productive than the grain rotation.

Studies at Whitefox

In 1936 a crop rotation experiment got underway at Whitefox, Saskatchewan, in which three rotations were compared. This study was fairly well designed and has produced interesting and useful data. The three rotations were compared from standpoints of crop yield, effect on soil structure, organic matter and effect on soil fertility. The rotations consisted of:

(a) A 3-year rotation; fallow, wheat, oats.
(b) A 4-year rotation; wheat, oats seeded down to grass-legume, hay, hay and break.
(c) A 6-year rotation; fallow, wheat seeded down to grass-legume, hay, hay and break, wheat, oats.

From a 22-year summary of this work (1936-1957), it was found that the three-year rotation, consisting of two-thirds of the area in grain and one-third in fallow, produced an average of 773 pounds of grain per cultivated acre. The comparable figure for the four-year rotation was 839 pounds. In this rotation one-half the land area was cropped to grain each year and the other half was in grass-legume hay. There was no fallow. In the six-year rotation the average grain yield, based on total land area, was 889 pounds per acre. In this case one-half the land area was in grain, one-third in hay and one-sixth in fallow. Thus, in both the four and six-year rotations
the two years of forage crops were in a complementary relationship with the grain. With only three sets of crop-fallow combinations compared in this study, it is not apparent at exactly what percentage level forages become competitive in a rotation under the environmental conditions that existed at Whitefox during the course of this study. It is apparent though, that the combination of fallow, grain and forage in the 6-year rotation is superior to the combinations used in the four or three year sequence. Besides the increased grain production the four-year rotation produced an annual average of .61 tons of grass-legume hay per acre of land area compared with .51 tons for the 6-year rotation. By applying the cost-price relationships prevailing during the course of this experiment, the twenty-two year average annual net profit per acre from the three-year sequence was $3.23 as compared with $9.50 from the four-year, and $11.11 from the six-year rotation.

Under conditions similar to those at Whitefox, an efficient grain farm manager might use these findings as a valuable guide when planning his cropping practice, but he would still like to know what was the optimum combination of fallow, grain and forage for maximum grain production. He known the six-year rotation is good, but is it the best? This is a basic question that agronomists in Western Canada are as yet unable to answer for most soil zones.

Although this experiment was somewhat better designed than many of the older ones, the findings must still be interpreted in a very general way. Gilson (28) critically examined this experiment from a design standpoint and was unable to determine the objective of the study. He asked,

"Was it to study (a) the effect of crop sequence on yield (b) the effect of varying proportions of hay in the rotation on grain yields, or (c) the effect of summerfallow on yields? Regarding the evaluation of the experiment Gilson suggests that, (a) the effect of summerfallow, hay and crop sequence are all confounded in the net result, and (b) costs should be reported as 'physical inputs' so that changing levels of costs could be used on the basic physical data."
Studies at Brandon

Although Brandon has a slightly higher average annual precipitation than either Indian Head or Whitefoxx, the long term comparative rotation studies at the Manitoba station do not indicate a complementary relationship between forages and grain (61). One reason for the comparatively good showing of the grain rotation at Brandon may be that these rotations are located on 'rich Assiniboine clay loam (8). Inasmuch as this soil is far from representative of Western Manitoba, this situation helps to emphasize the obvious fact that soils on which rotation studies are to be conducted should be selected with much care so that the findings from the experiment will be applicable in as large a surrounding area as possible.

Considering the rich clay loams on which the Brandon rotations were laid out, it is not surprising to find that the grain rotation produced an average of 1,092 pounds grain per acre over a 32-year period, compared with 712 pounds for rotation 'G' and 817 pounds for rotation 'H'. The "old Manitoba grain rotation" in this comparison consisted of: summerfallow (manured), wheat, wheat, oats; rotation 'G' was: corn-silage (manured), wheat, hay, hay and break, wheat, oats; and rotation 'H', summerfallow (manured), wheat, hay, hay and break, wheat, oats. Rotation 'G' and 'H' were identical except that in 'G' silage corn replaced the summerfallow and thereby decreased the grain production by 105 pounds per acre or by about 13 per cent. Thus, according to this observation, corn cannot be regarded as an effective summerfallow substitute under conditions prevailing at the site of this experiment.

However, from a practical standpoint it must be realized that the manager of a mixed farm with an important livestock enterprise is not only interested in maximum grain yields per acre, but must also obtain hay and silage. Thus, when placing fair values on all the grain and forage crops in the three Brandon rotations, the average profit per acre for the grain rotation was $3.58 compared to $5.22 for rotation 'G' and $5.41 for rotation 'H'. Here again, a general guide is provided for those seeking advice in establishing a cropping system on rich Assiniboine clay loam.
in the Brandon area. In all probability the results would have been quite different had the experiment been conducted on another soil type that had a different original fertility level and a different moisture retention capacity. Thus, the findings from this experiment may have rather limited application in Manitoba.

More recently, in 1949, another series of experiments were initiated at the Brandon Experimental Farm. These studies were of a somewhat more basic nature in that they attempted to establish which sequence of a given number and kind of cereal crops was the most productive. Some results from this study are referred to in Chapter 4. Similar studies are being or have been conducted at most of the other experimental stations in western Canada.

Studies at Lacombe

When moving westward from the dry central plains area to the Lacombe Experimental Farm (17.73 inches precipitation), in the black soil zone of Central Alberta, forage crops may again assume a complementary relationship with cereals in a grain rotation. Two long term experiments have been compared at Lacombe since 1912. Rotation 'C', fallow, wheat, wheat was located immediately adjoining the seven-year mixed farming rotation 'O', consisting of potatoes, wheat, oats, fallow, wheat, hay hay. Both rotations received an average of two tons barnyard manure per year. Interesting differences are now appearing between the long term and the shorter term, per acre, production from these two experiments. These differences are shown below.

<table>
<thead>
<tr>
<th>Average Grain Production in Pounds Per Acre (of Entire Production)</th>
<th>3 year</th>
<th>7 year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation 'C'</td>
<td>Rotation 'O'</td>
<td></td>
</tr>
<tr>
<td>34 yr. ave. (1912-1946)</td>
<td>820</td>
<td>904</td>
</tr>
<tr>
<td>10 yr. ave. (1937-1946)</td>
<td>726</td>
<td>1133</td>
</tr>
</tbody>
</table>

The above data clearly show that as the native fertility in the soils gradually depleted under the grain rotation 'C', the yields of grain decreased. On the other
hand, grain yields from the mixed farming rotation 'O' have steadily increased. Although a complementary relationship does exist between a grass-legume mixture and grain, the frequency at which such a mixture should appear in a rotation to affect optimum yield is still not known. Again one must remember that factors other than the complementary relationship of one crop to another should be taken into account when assessing the value of forages in a rotation. On a mixed farm forage crops would supplement the livestock enterprise and might be justified on that account. Furthermore, most workers attributed much of the value of forages in a rotation to their ability to maintain a more desirable physical condition of the soil, and thus reduce or prevent soil erosion and improve aeration and internal drainage. Some of these attributes are not immediately reflected in increased crop yields but nevertheless they do represent economic value over a period of time.

Summary and Conclusions

In the preceding paragraphs an attempt has been made to show from Experimental Farm investigations that a close relationship exists between the best cropping system for a particular area and the annual precipitation. Experimental Farms at Regina, Swift Current, Scott, and Lethbridge, that are located in the 13 to 15 inch precipitation region, found that a year of summerfallow was required every second or third year for best long term crop production. Rotation studies conducted either to the east or west of this semi-arid belt showed that summerfallow was required less frequently, if at all, for moisture accumulation, but was very useful for weed control and for the decomposition of heavy straw yields. These areas generally found that forage crops could complement grain crops in a rotation, especially if the experiment was located on a soil of medium to low native fertility.

More recently, crop sequence studies of a more fundamental nature have been undertaken at a number of Experimental Stations. At Swift Current, the most productive sequences of grain crops were those in which the crops were arranged in descending order of their water requirements, e.g. wheat, barley, oats. At Brandon, where moisture was not as limiting a factor as at Swift Current, the sequence, fallow, barley, wheat was more productive than fallow, wheat,
barley. Diseases on barley were noticeably more severe in the latter sequence, which might account for the superiority of the former. Studies of this type will be of considerable value to the farmer when planning his future year to year cropping programs. With constant variations in the cost and price relationships on the farm, the farmer must be able to be flexible in the type of crops he produces. Basic information, like the effect of one crop on another, allows him to be flexible and still follow the best cropping practices known.

Several other Western Canadian crop rotation experiments might have been referred to in the above discussion but little in the way of new concepts would have emerged, as many of the rotation experiments at the different stations, have, until recently, been basically similar.
Chapter 14

Management Practices of Manures

Many of the early crop rotation experiments were started in the days when horses represented the only source of farm power. Consequently manure was in abundant supply on most grain farms and efforts were made by Experimental Farms to determine its most efficient utilization. Several experiments were designed to study the effects on crop yields and net returns when manure was applied to the land at different stages in the rotation, and at different times of year, with various rates and methods of application. Although this information is still of interest to the mixed farm operator, the grain farmer using motor power will find it of limited value.

In July, 1920, Dr. J. H. Grisdale, Federal Deputy Minister of Agriculture appeared before the Commission on Conservation then sitting in Winnipeg. In his submission he presented information on the findings of Western Experimental Farms relative to the effects of barnyard manure, green manure and commercial fertilizers on succeeding crop yields (15). Most of these investigations were conducted as separate experiments and were not integrated with crop rotation studies. The tests conducted on five western Experimental Farms generally showed that barnyard manure increased succeeding crop yields, especially when applied and plowed under in the fall of the year.

The green manure trials produced less consistent results because it appeared that annual precipitation had a considerable bearing on the crop yield following the plowing under of a green manure crop. Grisdale reported that at Lethbridge the yields of grain from plots where peas and vetches were plowed under were 3 1/2 bushels per acre less than from bare fallow, and 5 1/2 bushels less than from fallow with a treatment of barnyard manure. Similar results were obtained from Lacombe and Rosthern. At Scott and Indian Head, the green manure treatment resulted in slightly higher yields than from bare fallow, but less than from fallow treated with barnyard manure.
Grisdale's statement to the Commission concerning commercial fertilizers is of interest:

"We also tried commercial fertilizers, which are practically unknown on these prairies, and I doubt if they will ever be very useful in the Prairie Provinces, at least not in this generation. The abundant quality in our soil, if satisfactory cultural methods are followed, will be maintained for many years to come."

He continued to point out that a considerable amount of moisture was required to render fertilizers effective, and therefore the future of fertilizers might be confined to areas under irrigation.

More recently a few of the stations have continued tests in which the effects of barnyard and green manures have been observed. Indian Head reported that, in a 21-year experiment, when plowing 8 tons of well rotted manure into summer-fallow, the following crop of wheat averaged about 2 bushels per acre more than wheat after fallow without manure (63). Brandon found that,

"The old Manitoba four-year rotation of fallow, wheat, wheat, oats, which has been on its present location since 1911, shows a long term average profit of $3.65 per acre on one-half of the rotation that gets 12 tons per acre of barnyard manure every four years. On the other half, where no addition of fertility of any kind has been made, the profit has been $3.70 per acre. Crops always yielded better on the manured side but not sufficiently to offset the cost of applying manure." (8, 37).

At Brandon, sweet clover plowed under as a green manure at early bloom stage has not benefited the succeeding crops of wheat and corn. On the light soils in the Brandon area barnyard manure has increased crop yields to a greater extent than have commercial fertilizers and green manure. Measured in terms of net profits, none of the treatments appreciably increased monetary returns per acre (60).

Several of the long term fertility experiments
conducted by Professor Ellis at the University of Manitoba included studies on the management of manures. A 30-year study that compared seven different methods of applying barnyard manure indicated that the method of manure application does not appreciably affect the yield of succeeding wheat crops (27). Another 26-year experiment was conducted to measure the effects of manure applications that varied in rate from 5 tons to 30 tons when applied every four years on a fallow, wheat, corn, wheat rotation. All manure treatments were applied to the wheat stubble after the fallow year. Yields of corn after wheat appeared to respond to all rates of application, but especially to the higher ones. Residual effects of manures were noted up to four years after application. Another 20-year experiment in which each plot in a corn, wheat, wheat rotation received an equal amount of manure showed that there was no difference in wheat yields due to varying the amounts of manure applied at a prescribed time. In another 6-year rotation, manure was applied at various places in the rotation at the rate of 12 tons per acre. However, the 19-year average yields of hay and grain indicated no preferred place in a rotation for applying barnyard manure.

In another University of Manitoba test, a 4-year fallow, wheat, corn, wheat rotation was employed to determine the long term effect of green manures on succeeding wheat yields. The green manure crops compared were weeds, spring rye, buckwheat, corn, peas, sweet clover and red clover. Twenty-nine years of data indicated that on the average, wheat yields on green manure did not vary more than one bushel per acre from the check plots. However, the one plot that received rotted barnyard manure increased the wheat yield by 16 per cent over the check plots. It should be borne in mind that these University of Manitoba fertility studies were conducted on a fairly productive Red River clay soil.

Only a few brief references have been made in this discussion concerning the effects of commercial fertilizer applications at varying stages of different crop rotations. A detailed discussion on the relationships and interactions of chemical fertilizers and crop rotations would go beyond the intent and scope of this study and therefore is not included in this discussion.
PART FOUR

A CRITICAL VIEW—PAST and FUTURE

Chapter 15

Crop Rotation Studies: A Critical Appraisal

Perhaps few subjects of agricultural investigation are more complex, require as long a time to complete and are more subject to misinterpretation than is the area of crop rotations. Thus, it might follow that few fields of study are more severely criticized. No purpose would be served by critically examining, in the light of today's knowledge of science and biometrics, the crop rotation experiments that were designed and established in the light of scientific knowledge available in 1911. Obviously these experiments were set out to obtain information badly needed by nearby farmers, and likely were never intended to be basic scientific studies for publication in professional journals. Replication and randomization of treatments was unknown to our pioneer rotation workers of 1911. These accepted experimental procedures of today were first utilized in rotation studies by Fisher, at Rothamsted, in 1920. Thus, the imperfections of the agronomic experiments conceived in the first two decades of this century are readily excusable.

However, this does not explain why rotation experiments laid down in the 1920's, the 1930's and the 1940's remained basically similar in design to those established in 1911. It has also appeared that as the years have gone by, many agronomists have acquired an ever increasing faith in the data acquired from experiments with statistically unacceptable designs. Furthermore, agronomists continue to draw firm conclusions between non-replicated rotations laid down in 1911, even after it is well known that parts of the same experiment were laid down on distinctly different soil types. Quotations from Page 8 of the 1947 to 1956 Progress Report of the Indian Head Experimental Farm serve as an example.

"Crop rotation experiments have been carried out continuously on the Indian Head Experimental Farm since 1911 and as some of these rotations have remained
unchanged for many years considerable data have been accumulated....The 3-year rotation was compared with the 9-year rotation for 45 years....The 3-year rotation is on Indian Head clay whereas the 9-year rotation is on a more productive soil, classed as heavy clay. Unfortunately the land in the 3-year rotation is slightly undulating and some topsoil has been lost as a result of wind and water erosion, but in the 9-year rotation, erosion has not been a problem."

Most workers, however, have come to recognize the need for a more basic and more scientific approach to the study of crop rotations. In 1951, Hill (38) wrote a paper entitled, "Modifications of the Randomized Block Design for Crop Rotation Experiments". In this paper the author reviews the practical and statistical deficiencies of the conventional, non-replicated rotation experiments and then outlines in detail, a statistically acceptable design whereby several rotations may be validly compared. Since 1951, rotation experiments following Hill's design have been established at Lethbridge, Regina, Scott, Lacombe and Melfort. The University of Saskatchewan's Field Husbandry Department has also patterned rotation studies after the modified randomized block design (29).

The problem of adapting research of an applied nature to scientific disciplines is fortunately not confined to the study of crop rotations. After reviewing more than 500 published papers, Leonard A. Salter Jr. wrote a comprehensive critical analysis of research reports on Land Economics (74). Several of the author's general conclusions on the common faults of many social science research publications seem to apply as well to a large proportion of crop rotation studies of the past. A few of these observations follow.

"The objective of much research is no more clearly defined than 'to present materials that may be of interest to others'. With such a compass the outcome of the work is merely the presentation of a mass of data, the relevance of which to the problematic may be great or small but is not indicated in either case."

"Interest centers almost entirely on the techniques of handling collected information and that scant attention
is given to the problems of research that precede the arrangement of collected data even though these determinations are said to be of utmost importance."

"Unfortunately, however, it is more common for pieces of research to be repetitive rather than progressional."

Judging from the scores of rotation reports the writer has reviewed, these comments apply as well to many of the research reports on crop rotation studies.

Problems Inherent in Crop Rotation Studies

Most of the problems associated with long term crop rotation studies may be classified as being caused by (a) personal factors (b) climatic variations, and (c) the time aspect of the experiment.

Personal Factors

The most important personal factor is the planning and thought that goes into the experiment before field work is started. Although the importance of the initial design has been repeatedly referred to, a summary of this all important personal factor seems in order.

(i) Obviously the purpose of the experiment should be clearly stated. The hypotheses that is to be tested should be outlined. Each experiment should either search for a new 'basic principle' or test an existing principle in an untested environment, rather than just produce data, "that may be of interest to others".

(ii) The design of the experiment should have the same clarity and singleness of purpose as the initial statement of purpose. One experiment should not be "overloaded" so that the intended objective cannot be clearly measured because of having been confounded with minor side issues. Rather than overloading one experiment, two or more experiments should be set up if several objectives are being pursued. Obviously the design should be statistically acceptable. This, of course, requires a replication.
and randomization of treatments.

(iii) The proper type of data should be recorded. The conventional cost, returns and net profit data are of little value in a short term rotation study and of even less value in a long term study. The costs and prices recorded in the literature of rotation studies conducted in the 1930's are of no value today. If workers recorded basic production inputs and outputs that could be converted into current costs and prices at any given time, the data would serve a useful purpose.

(iv) Crop rotation experiments require much time to produce worthwhile information and therefore become very costly. As resources are limited, a worker must use his best judgment as to how these resources should be expended. For example, considering the limited resources available, the worker must decide on how many soil zones within Manitoba rotation studies should be undertaken. He must also determine whether a study should be of an intensive or extensive nature. The personal factor may also help to confound a long term rotation study when a new worker takes over the direction of a half completed experiment from the retiring founder of the project. For instance, one worker might prefer early seeding whereas the other has a personal bias toward later seeding. One may use chemical pesticides while the other preferred not to use them. Situations like this have arisen in rotation studies and have contributed to producing data of questionable value.

Climatic Problems

Several of the complicating factors associated with rotation studies in Western Canada can be attributed to climatic extremities and irregularities, particularly temperature and rainfall. The northern climate of the Canadian prairies limits the variety of crops that may be grown. Because of these prevailing conditions it is not practical to introduce and apply rotation practices from areas further south that produce a greater variety of crops under more stable and predictable temperature and rainfall conditions. In Chapter 10 attention
was drawn to the extreme year to year variation in annual precipitation on the western prairies. Chen and Arny's findings that different climatic conditions affected a number of crops differently at various periods in the growing season was referred to in some detail in Chapter 3. Thus, in many rotation experiments it is likely that crop differences have been attributed to rotations that were really due to aspects of moisture or temperature.

The Time Element

The length of time required to produce worthwhile data and the much longer time required to complete a crop rotation experiment presents a number of problems for the rotation worker. In a number of instances the person who designed and initiated the experiment is no longer on the job when the project comes to an end. Thus, another worker is required to interpret the objectives of the experiment and draw conclusions from the available data. Here the personal and the time aspects might well introduce an element of error. For a long term experiment to be realistic, it may be required, from time to time, to change some cropping practices in the middle of the experiment in order to keep abreast with technical advances on the farm. If innovations like chemical weed, insect or disease control measures were introduced in the middle of a rotation experiment, the entire project might be confounded. On the other hand, if they are not introduced the project may be obsolete long before it is completed. For example, rotation experiments at one time took into account feed requirements for a dozen or more horses on the farm. When farms became mechanized during and after the second world war, horses were no longer required. Thus, a number of long term projects have been carried on for years, even though they were completely obsolete in terms of practical usefulness.

Thus, the study of crop rotations is perhaps the most complex of all fields of biological research, for in this area of investigation a number of disciplines in the physical, biological and social sciences interact for a score or more years. Certainly a well conceived approach to a crop rotation study is essential to assure even a reasonably reliable conclusion.
Chapter 16

A Suggested Direction for Future Research

From the impressions gained during this extensive review of literature, and from numerous discussions with fellow agronomists, some thoughts have arisen as to the most productive emphasis in future crop rotation research.

The writer firmly believes that the time has arrived when further rotation studies should be "progressional" rather than continue to be "repetitive", as has been the case to a large extent in the past. Therefore, it seems reasonable to suggest that a minimum of additional resources need be utilized for further general, long term comparisons between the three-year, six-year and eight-year types of rotations. However, a limited number of these standard rotation comparisons on a few strategic soil types would still be of interest in order to observe the rate of soil organic matter and nutrient depletion, and to note, periodically, the effect of long term cropping on soil structure.

Most workers would agree, however, that the general direction of future crop rotation studies should be directed towards solving specific problems that are basic to the planning of a sound, flexible cropping system. In a time of rapidly changing marketing conditions, the only practical cropping program is one with built-in flexibility. The ability to adjust rapidly to changes in the cash market for farm products is becoming ever more important, as farmers now require more cash than they did some years ago, in order to purchase an increasing number of products which at one time they obtained by processing the products they themselves produced. A fifty-year comparison between a two, four and eight year rotation will be of little value to a farmer who must frequently shift his production pattern to keep in step with market demands and ever-changing government price and production policies. To be flexible in production and still be efficient, a farmer needs to have a large number of basic facts at hand that may be used as required. Some of these needed facts, which might well be objects of future research, are listed below.
Soil Moisture

Much research has already centered on this topic. However, to date the evidence is not clear as to whether or not it is in the interests of efficiency that about 23 million acres of productive farmland lie in black fallow each growing season. As chemicals become available to control weeds and insects, the farmer would like to know in which regions of Western Canada summerfallowing for moisture conservation alone is economic, how frequently such land should be fallowed, and by which method. An intensive rather than an extensive approach to this problem is required. Findings from such a study should be of a fundamental nature so that they could be applied to all western Canadian farming conditions. If farmers knew the facts as to the complementary or competitive relationships of summerfallow on their farms, far reaching changes in the cropping pattern might result.

Soil Nitrogen

Nitrogen as well as moisture is a limiting factor to optimum plant growth in many areas of Western Canada. Again, much effort and research has already gone into the study of nitrogen relationships but several areas of basic importance are still unexplored. For example, how much nitrogen is released in the soil during a year of summerfallowing? How much of this released nitrogen, if any, is lost? Does soil texture affect nitrogen loss? Are there any cropping or cultural practices that could reduce such a loss?

A farm manager would also like to know the substitution relationships between nitrogen supplied by legumes and nitrogen supplied by chemical fertilizers. Differently stated, how much of the increase in crop yield following a legume (where such is the case) can be attributed to the nodule nitrogen and how much is due to the effects of the legume on the physical properties of the soil. From such a study the value of a legume in a rotation could be broken down into its component parts. Such information might reveal that under conditions of fair soil structure the potential value of a legume in a rotation could be much more cheaply realized by a prescribed application of a nitrogen fertilizer.
Complementary Forage Relationships

To date little more than rough estimates are available as to the complementary position of forage crops in a grain rotation for specific soil types. It is well known, for example, that on a grey-wooded soil the complementary ratio of forage crops is much higher than on a well-drained black earth. But the optimum percentage of forage for grain production on soil associations of either soil type is still indefinite. To obtain reliable data of this kind for only a few of the major agricultural soil types of Manitoba would be an ambitious undertaking. But without this information the manager of a grain farm may well waste valuable land resources by overseeding to forage crops for which he has no market or he may deplete his soil by cropping too frequently before seeding down to forage. In both cases he would not be utilizing his land to best advantage. This type of data concerning complementary-competitive forage relationships is essential to planning a profitable cropping program under the competitive conditions presently prevailing in agriculture.

Crop Sequence

In order to efficiently adapt and adjust a cropping system to meet market requirements, a farmer must have information as to the best preceding and succeeding crop for each crop he is raising. Evidence from crop sequence studies at Brandon would suggest that experiments of this kind should be repeated periodically, because, as new varieties of a crop replace old ones the preceding and succeeding status of the crop may have been effected. As outlined in Chapter 10, the reason why the fallow, barley, wheat sequence has been more productive at Brandon than fallow, wheat, barley is believed to be related to the susceptibility of present barley varieties to leaf diseases. Apparently diseases of barley are aggravated when the crop is seeded on stubble. Disease resistant barley varieties might alter the best position for barley in such a sequence. Reference was also made earlier to workers in Germany who had devised charts showing the best preceding and succeeding crop relationships for all crops of importance to the area when grown in several soil and climatic zones. Information like this would be most helpful when operating a flexible cropping program.
Effect of Straw on Soil Productivity

An intensive research program might also be directed toward isolating and evaluating the factors responsible for depressed grain yields following a heavy straw crop. Evidence from some recently conducted experiments would indicate that the yield depression of grain seeded on heavy stubble is due entirely to the physical effects of the stubble on the seedbed, rather than to the widening of the carbon-nitrogen ratio. If this is true, a serious reappraisal of fertilizer, tillage and rotation practices would be in order. Information is also needed as to the relationship of straw and crop cover to soil moisture, soil temperature and weed growth. If crop cover is found to affect micro-climatic changes in the soil, we should know how these changes influence plant growth? Many of these very basic questions of vital significance to field scale production of crops are not yet known.

Monoculture

Perhaps in the light of recent advances in pest control and in the interests of efficiency through specialization, another close look should be taken at the possibility of continuous cropping - under a prescribed set of circumstances. In Chapter 2 a number of obvious advantages of monoculture were outlined. Although this suggestion might cause some alarm, it should be remembered that most of the wheat, cotton and rice produced throughout the world is continuously cropped, except for the summerfallow years, where fallowing is practiced. Continuous cropping is the only practical way of farming in areas where the soil and climate are suited to the production of only one commercial crop. In certain areas of the United States, particularly in the corn and soybean growing areas there has been a recent trend in this direction. Kommedahl and Wilcoxson (43) of Minnesota wrote as follows in the November 1959 issue of Crops and Soils.

"Recent trends in certain crops have, however, resulted in continuous cropping - and less crop rotation - ."

An objective, critical reappraisal of monoculture as it might apply to Manitoba appears justified in the light of recent technological and economic aspects of modern agriculture.
In summary, the objective of future research in crop rotations should be that of obtaining specific units of basic information. An intelligent farm manager should then be able to use these agronomic "links" as he needs them to plan and operate a versatile cropping program that can quickly adjust itself to changing economic or political conditions.


36. Hedlin, R. A., R. E. Smith and F. P. Leclaire. Effect of Crop Residue and Fertilizer Treatments on the Yield and Pro-


40A. Kellogg, C. E. We Seek; We Learn. Soil, Yearbook of Agriculture. pp. 1-5. 1957.


- 85 -


