Selected Articles.

Irrigation and Crop Production.*

Introduction.

CROP yield can be regarded as a measure of the success of agricultural operations in overcoming factors limiting plant growth. Under natural conditions, systems of agriculture which give optimum yields have been developed as the result of experience, the system representing a condition in which the factors operating for and against crop yield have been stabilized.

The introduction of a system of perennial irrigation has frequently been followed by a reduction in crop yield, the yield probably becoming stabilized at a point below the optimum. This indicates that under the artificial conditions of irrigation the balance of the factors determining crop yield is disturbed, or new factors operating against crop yield are introduced. In some cases this may be attributed to the accumulation of salts, such as sodium chloride, in the soil, but in others, the reason for the decline in yield is not so obvious. A thorough knowledge of the agricultural conditions imposed by a system of perennial irrigation is of great importance if crop yields are to be maintained. This is particularly the case at the present time, in view of the fact that irrigation systems are being developed on a large scale in the British Empire.

The climatic conditions determining plant growth are rainfall and temperature. If the temperature is suitable and there is an adequate rainfall, plant growth will take place. If either the temperature is unsuitable or the rainfall is deficient, plant growth ceases. Irrigation is therefore practised in areas where the temperature factor for growth is favourable, but the rainfall badly distributed or deficient.

Irrigation may be regarded from two points of view: the engineering, dealing mainly with the problems of the storage and distribution of water, and the agricultural, dealing with the use of the stored water. As a rule, irrigation is mainly considered from the engineering standpoint, the amount of water stored and the area irrigated being taken as the index by which the success, or otherwise, of the irrigation scheme is judged. This would be a legitimate conclusion if water were the only factor that could limit yield. But since crop yielded is largely influenced by soil conditions—chemical, physical, and biological—and since the soil serves as the medium through which the plant obtains the water supplied by irrigation, it is necessary to consider the effects of irrigation on the soil if the factors determining the efficient use of an irrigation system are to be thoroughly understood. Again, irrigation necessitates an alteration in the agricultural system of the irrigated area by the introduction of further crops into the rotation. The introduction of these

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crops reacts on the agricultural system as a whole, and may necessitate alterations in cultural conditions. A further point that must also be considered is the alteration in the climatic conditions—the soil climate and crop climate—in the irrigated area, and the effect of these changed conditions on plant diseases and insect pests. It will be seen, therefore, that before an expensive system of irrigation can be introduced with confidence a large number of interdependent factors must be taken into consideration. At the present time, little is known of the relation of irrigation to these factors, and hence crop production under a new system of irrigation has not a solid foundation. The true index of the success or otherwise of any irrigation scheme is to be found, not in the amount of water stored and distributed, but in the yield of crops which result from the use of the stored water. The results of the development of the system of perennial irrigation in Egypt have shown that the storage of increasing quantities of water is not necessarily followed by corresponding increases in the yield of the irrigated crops. On the contrary, the increases in stored water which have been made since the beginning of this century have been followed by marked decreases in yield. The development of an irrigation system is costly, and it is introduced with the object of growing a crop of high value; the importance, therefore, of a knowledge of the factors determining crop yield under irrigation is obvious. In the present paper, some factors influencing crop yield under irrigation will be considered.

Crop Rotation and Irrigation.

The development of a system of irrigation can alter the crop rotation in two ways—(a) by the introduction of further crops into the rotation, and (b) by the alteration of the conditions of cultivation of the crops. As the development of the system of perennial irrigation in Egypt affords instances of both of these alterations, they will be illustrated by considering the effect of irrigation on the agriculture of that country.

In order to appreciate the agricultural conditions now existing under perennial irrigation, it is necessary to deal briefly with the history of irrigation in Egypt. From an agricultural point of view, Egypt is rainless except in the neighbourhood of the Mediterranean coast. The production of crops in Egypt has, therefore, always been dependent for water supply upon a system of irrigation. One of the chief characteristics of the Nile is the annual flood, due to rain on the Abyssinian plateau. The flood begins to reach Cairo at the end of July, and is at its height about the end of September. The first type of irrigation used in Egypt was that known as basin irrigation. The land under this type of irrigation was divided into a series of basins by means of dykes. The flood water was led by natural channels or artificial canals into the basins, and allowed to stand in them for a period of about forty-five days. The retention of the water in the basins for this length of time resulted in the thorough saturation of the soil, and at the same time the silt held in suspension was deposited. At the end of the period of forty-five days—that is, in November—the water was run out of the basins into the river, and the land was sown with winter crops. The crops were dependent for their water supply on the subsoil water left as the result of the inundation. The crops were harvested in April and May, after which the stubbles remained fallow until the following flood period in September. One of the main features of the basin system of irrigation was the maintenance of soil fertility as indicated by the constancy of the crop yields. Two characteristics of the basin system of irrigation may have been responsible for the maintenance of soil fertility—(a) the annual inundation during which the land received a deposit of Nile silt, and (b) the annual fallow period from May till September.

Until recently it was considered that the main factor responsible for the maintenance of soil fertility under the basin system of irrigation was the annual deposit of Nile silt. Experiments recently carried out in Egypt have shown, however, that Nile silt has little manurial value, and that no increase in yield follows a dressing of fresh Nile silt. The cause of the maintenance of the fertility of the soil must, therefore, be sought in the annual fallow period.

The fallow period may be divided into two distinct portions: the first during which the soil is dried and cracked, and the second, during which the soil is heated. The drying and cracking of the soil is almost complete before the winter crops are harvested. This drying and cracking of the soil has recently been regarded as of fundamental importance in maintaining soil fertility. Under perennial irrigation, the soil on which cotton is grown receives the same amount of drying and cracking as it did under basin irrigation, yet there has been a decline in the yield of cotton. It follows, therefore, that the drying and cracking of the soil have not the *fundamental* importance attributed to them, though they may be beneficial. Investigations on the effect of the heating of the soil during the fallow period have recently been carried out, and indicate that it is due to the heating which the soil received that soil fertility was maintained under the basin system of irrigation. Soil temperatures have been continuously recorded in fallow land from May to September. As a result of the study of these, it has been shown that partial sterilization of the soil due to heat does take place. Further, it has been shown that the partial sterilization of the soil is mainly confined to the period July 1 to August 15. Field experiments on cotton, to be mentioned later, have shown that the yield of cotton is higher when the cotton is sown on land that has been fallow in July and August than when it is sown on land with the fallow curtailed to June 30. The maintenance of soil fertility under basin irrigation must probably, therefore, be attributed to the heating of the soil during the period July 1 to August 15. This is an important conclusion, as will be seen in the discussion of the changes in the agricultural system with the development of perennial irrigation.

The objection to the basin system of irrigation is that the whole of the land is idle for a considerable portion of the year during which the temperatures are suitable for plant growth. The remedy is to supply water by a system of perennial irrigation. The object of perennial irrigation was the introduction of summer cropping and the reduction in the fallow area. The development of the system of perennial irrigation will now be discussed.

Until 1820, such irrigation as was practised in the Nile Delta was of the basin type. The possibility of growing cotton in Egypt was recognized by Jumel. As cotton could only be grown as a summer crop, a water supply was necessary for irrigating the crop. Perennial irrigation was, therefore, established in 1820, with the object of growing cotton. The Nile is low during the summer period, and the channels used for filling the basins were not deep enough to carry water in the low stage of the river. The first step, therefore, in the development of the system of perennial irrigation was the deepening of the channels to take the low level summer water of the Nile. These deep channels had two objections—(1) the whole of the water used for irrigation had to be lifted a considerable distance on to the land, and (2) the canals used to silt up during high Nile, necessitating an annual clearance entailing the use of a large amount of labour. In order to overcome these difficulties, the construction of the Delta barrages was sanctioned. The barrages were commenced in 1835, and were first used in 1861, but owing to difficulties that arose, they were not of great value to irrigation until 1884. During the period 1835 to 1884, perennial irrigation was practically maintained by the annual clearance of the deep canals by forced labour. The main developments in the perennial irrigation system have taken place since 1884. In that year, both barrages were used for the first time. In 1891 repairs to the barrages were completed, and they held up 13 metres of water on the gauge. Between 1891 and 1900 the barrages held up 14 metres, and, since 1901, 15·5 metres on the gauge.

The main result of increasing the amount of water held up at the barrage has been to convert the country from lift to free-flow irrigation. Since 1901, the perennial irrigation system in Egypt has undergone two further developments. In 1903, the water stored by the Aswan Dam was added to the summer supply of the Nile, and in 1906 it was decided to raise the Aswan Dam so that more water could be stored; this additional supply was added to the river in 1912. As an index of the success or otherwise of the development of the perennial irrigation system, the effect of its development upon the yield of cotton will be considered.

The yield of the first cotton crop in Egypt was about 1,000 kantars. Between 1877 and 1883, the average yield was maintained at 2,500,000 kantars, which represents an average yield per feddan of 3 kantars. The barrage at this time held up 12·5 metres on its gauge. Between 1884 and 1890, it held up 13·0 metres, and the area under cotton increased to 900,000 feddans, with an average yield of 3·5 kantars per feddan. Between 1891 and 1900, the barrage held up 14 metres on its gauge, and the average yield of cotton during this period reached 5·5 kantars per feddan. In 1901, it held up 15·5 metres on the gauge and the average yield fell to 4·9 kantars. In 1903, the water stored in the Aswan Dam became available, and the average yield between 1903 and 1910 fell to 4·5 kantars per feddan. Since 1910, further decreases in the average yield of cotton per feddan have occurred, though now the yield seems to be stabilized.

From 1820 to 1900, each addition to the summer water supply has been followed by an increase in the average yield of cotton per feddan. The development of the system of perennial irrigation which took place during this period must be regarded as having been successful. The development of the irrigation system since 1900 has been followed by a decrease in the average yield of cotton per feddan; developments during this period have, therefore, not been successful. During the successful period of development, as each addition to the water supply was followed by an increased yield, water must have been the principal factor limiting the production of cotton. During the period of unsuccessful development, since additions to the water supply are not followed by increased yields, some factor other than water supply, but dependent for its action on water supply, must be limiting the production of cotton. A study of the agricultural changes which have followed the developments in the perennial irrigation system indicates the cause of the decline in the yield.

Under the basin system of irrigation, winter crops only were grown. With the introduction of perennial irrigation, it became possible to cultivate an autumn crop in addition to the winter crops, as the land could be irrigated instead of inundated. Maize was, therefore, introduced. Before the land can be prepared for maize, it must receive an irrigation, since it is impossible to plough the land in the dry state following the summer fallow. Before 1900, the date on which the irrigation for ploughing the fallow land took place depended entirely upon the date on which the annual Nile flood had reached such a height that free-flow irrigation became possible. This date occurred in the month of August. Maize sowing before 1900, therefore, took place between August 10 and September 15. As a result of this, the land on which maize was sown had been fallow from May to August. As cotton is sown in February on land which carried maize the previous autumn, the cotton before 1900 was always sown on land that had been fallow the previous summer. Under these conditions, the fertility of the soil, as indicated by the yield of cotton, was maintained.

Since 1900, a change has been introduced into the method of using the stored water. The Irrigation Report for 1897 states: "It is further intended to raise the gates of the existing barrage so that a water level of 15·5 metres may be maintained. Early sowing of maize will be greatly facilitated, and all possible advantage taken of the rising flood." The water at the barrage was retained at 15·5 metres in 1901, and immediately the yield of cotton fell. The Irrigation Report for 1904 states that the fallow ended on June 15, The Report for 1909 definitely states the policy of the Irrigation Service as follows: "The tendency is to hold the reservoir supply later and later every year, so that the mass of the water is employed to augment the early stages of the flood rather than to increase the volume of the river at its lowest. The object of the Irrigation Service was, therefore, to use the stored water to obtain an artificially early flood in the river so that maize could be sown early. It is not generally realized that the object of storing water in Egypt is not now the irrigation of cotton, but the preparation of the land for early sowing of maize.

It will be seen that since the conversion of Egypt from basin to perennial irrigation, two changes have taken place: (1) increase in the amount of stored water; and (2) a change in the method of using the stored water. The first is an engineering question, but the second, the change in the method of using the stored water, is essentially agricultural. So long as perennial irrigation remained an engineering problem, it was successful, increases in available summer water being followed by increases in the yield of cotton. As soon as an alteration was made in the agricultural system by the introduction of a new method of using the stored water the yield fell. To the alteration in the agricultural system must be attributed, therefore, the decline in the yield of cotton.

A consideration of the crop rotations under basin irrigation and under the two main periods of the development of perennial irrigation show the main change that has taken place. A comparison of the crop rotation is shown below:—

Basin Irrigation	Perennial Irrigation (Before 1900)	Perennial Irrigation (After 1900)
May to August: fallow.	May to August: fallow	June to September: maize.
August to November: land flooded.	August to November: maize.	October to February: berseem.
November to May: wheat, beans, berseem.	November to February: berseem.	February to October: cotton.
May to August: fallow.	February to October: cotton.	October to May: wheat, beans, berseem.
	October to May: wheat, beans, berseem.	June to September: maize.
	May to August: fallow.	

From a comparison of the crop rotations, it will be seen that under basin irrigation the land was fallow every year between May and August. Under perennial irrigation prior to 1900, cotton was always sown on land that had been fallow from May to August the previous year. During this period of the development of the perennial irrigation system, summer fallow from May to August was still a characteristic feature of the agricultural system. Since 1900, however, the summer fallow has been completely eliminated from the agricultural system, so that the land is now continuously under crop. The change can be expressed as a "crop intensity factor," that is, the percentage of land under crop in July. This is shown in the following table for the provinces of Lower Egypt:

Percentage of Land under Crop in July in the Mudirias of Lower Egypt.

Year	Menufia	Qaliubia	Sharkieh	Daqahlia	Behera	Gharbia
1899	33 ·7	32 ·3	44 :0	67 ·0*	52 ·6*	49 ·4*
1913	99 :1	93 :3	96 ·3	95 :5	85 ·6	88 ·0

* Including rice.

While the increase in the area under summer crops in July is to some extent due to the increase in the area under cotton, it has mainly resulted from the early sowing of maize. It will be seen from these figures that the land is now completely under crop in July, while formerly, during this month, it was fallow. The importance of the fallow period, July 1 to August 15, has already been indicated in considering the maintenance of soil fertility under basin irrigation. The importance of this period in maintaining the yield of cotton was demonstrated in a series of field experiments. In one series of experiments maize was sown early, and in another series maize was sown in August, the whole of the land coming under cotton the following year. After a short fallow, the average yield of the plots was 3·40 kantars per feddan of cotton; after the long fallow, the yield of cotton was 4·39 kantars per feddan. Both the laboratory and field experiments demonstrate the value of the period July 1 to August 15 in maintaining soil fertility. To the elimination of this portion of the fallow by the alteration in the method of using the stored water must be attributed the decline in soil fertility under perennial irrigation as evidenced by the yield of cotton.

The change in the method of using the stored water may be justified from the point of view of food supply. Experiments on the effect of the sowing date on the yield of maize have shown that the maximum yield is obtained when the maize is sown in July. Against the decline in yield of cotton must, therefore, be set the increase in the yield of maize. The experiments indicate, however, that the gain in maize yield does not compensate for the lower yield of cotton, owing to the difference in the money values for the two crops.

The foregoing discussion of the changes that have taken place in the agricultural system of Egypt following the developments of perennial irrigation shows that the factors upon which soil fertility depends must be determined before an irrigation system is developed and retained as essential parts of the new agricultural system. It follows that the result of perennial irrigation cannot be perennial cropping, as has been attempted in Egypt.

The Quality of Irrigation Water.

Irrigation water is not pure water, but a dilute solution of salts. This solution has a seasonal variation, both in concentration and in the nature of the salts in solution. These variations may be illustrated by the seasonal variations in the composition of the Nile at Cairo. During the flood period, the amount of salts in solution is at a minimum. From December to May, there is a gradual increase in the concentration of sodium chloride which reaches a maximum of about fifty parts per million. During the summer months, sodium carbonate makes its appearance in the water, which becomes distinctly alkaline. The composition of the Nile water may be important in connection with the alteration that has been made in the method of using it. Formerly, this alkaline water was used for irrigating cotton—that is, a soil that was biologically active. Under these conditions, the sodium carbonate in solution would be rapidly converted to sodium bicarbonate, and "soil deterioration" would be unlikely to result. The present method of using the water is to irrigate a soil that is biologically dormant and hence carbon dioxide production in such a soil would be at a minimum. The result is that the sodium carbonate in the irrigation water remains as such until sufficient time has elapsed for the generation of carbon dioxide to convert it into the bicarbonate. As alkalies deflocculate clay, there will be undoubtedly a temporary deterioration in soil condition which in time may become permanent.

The effect of salts on plant growth has been mainly studied in water cultures or by adding salts in pot experiments, the results being expressed as the toxicity of the salt. If the soil were composed entirely of non-reactive material, these investigations would give results capable of direct application in the field. When a salt is added to a soil, base exchange takes place and, in nature, some of this base exchange may be either removed or decomposed by the addition of water. The effects of washing out large quantities of salts from a soil, the mode of origin of alkaline soils, and the general behaviour of soils when treated with strong salt solutions, are now fairly well understood. Investigations now being carried out at Cambridge show that with dilute solutions of salts, such as are used in irrigation, secondary reactions set in which alter the results that would be expected from a study of the action of concentrated solutions. As the subject is still under investigation, one point only will be mentioned.

The decline in the crop-producing power of soils under irrigation has frequently been attributed to the action of the salts in the irrigation water. In order to obtain information as to the effect of dilute salt solutions on soil, solutions of sodium chloride varying in concentration from 0 to 200 parts per million were allowed to percolate, under a constant head, through a series of soils, and the rates of percolation observed over a period of some months. The type of percolation curve obtained depended on the concentration of salt solution used. With pure water there was a gradual reduction in the rate of percolation to a stationery figure, the curve being smooth. Solutions varying in strength up to seventy-five parts per million sodium chloride produce a percolation curve which is a wave—that is, the rate of percolation decreases and increases periodically, the percolate at times containing colloidal clay. The final rate of percolation of this type is high. The rate of percolation of solutions between 100 and 200 parts per million sodium chloride is much higher than that of pure water or the more dilute solutions, the curve not being wavy, but showing a gradual decrease in the rate of percolation. The percolate in this case never contains colloidal clay.

The conclusion indicated is that with solutions less than 100 parts per million sodium chloride, base exchange takes place, but the solution is not of sufficient strength to prevent the hydrolysis of the sodium-clay. The final result is that a sodium-clay soil cannot be produced as the result of the percolation of dilute solutions. With higher concentrations of sodium chloride, hydrolysis of the sodium-clay produced by base exchange is impossible, and hence the sodium tends to accumulate, producing a sodium-clay soil. It appears that, providing an efficient drainage system is supplied to prevent salt accumulation, no soil deterioration need take place with suitable irrigation water. If drainage is not supplied, salt accumulation will take place, sodium-clay will be formed, and soil deterioration will result.

Irrigation and Drainage.

While the main effect of drainage in removing water from the soil is well known, the water conditions in an undrained soil have not been thoroughly studied. Investigations on drainage now being carried out at Cambridge have an important bearing on the relation between the irrigation water supplied and its effect when it has once entered the soil.

Drainage has usually been studied by means of lysimeters or drainguages. A lysimeter consists of an isolated block of soil supported on a perforated iron plate. The water draining from the block of soil as the result of rain falling on the surface can be collected and measured. By means of the lysimeter, the relationship between the rainfall and the amount of drainage can be studied.

The conditions established in lysimeters are those in a perfectly drained soil, and do not represent natural underground conditions. Under natural conditions, water applied to the surface of the soil does not immediately pass into the drains. It causes a rise in the subsoil water-table, the duration of the rise being dependent upon a number of factors, such as soil type and position.

In order to determine the effects of drainage, the result of adding water to the surface of an undrained soil must be studied. The method adopted in the investigation under discussion is to study, in an undrained soil, the effect of adding water to the surface on the subsoil water-table.

The first result of this study has been to show that 1 inch of water placed on the soil surface raises the water-table 4 inches. This is readily understood when it is considered that the water on entering the soil can only occupy the pore spaces. As the amount of pore space in the soil investigated was about 25 per cent. the rise in the water-table was four times the depth of water applied at the surface. This experiment was carried out on an undisturbed soil in the field. If arrangements are not made to control this rapid and large rise in the subsoil water-table, the soil soon becomes water-logged.

A second important result of this investigation is that the rise in the water-table commences immediately water is placed on the soil surface. The water placed on the surface does not flow through the soil to the water-table, but *displaces downwards the water already present in the soil.* The water reaching the water-table is, therefore, the solution which formed the nutritive medium for the plant or, in some cases, contained harmful salts. These results have a direct application to drainage under irrigation. Under irrigation, salts are added to the soil in the irrigation water. If concentration be prevented, soil deterioration will not take place. As the addition of irrigated water to the surface will displace the salt solution, if drainage has been provided, the salts added during one irrigation can be thus displaced into the drains at a subsequent irrigation. The problem involves an investigation of the depth of drainage, the frequency of irrigation, and the quantity of irrigation water to be used. As the soil solution containing the soluble plant food will also be displaced, a consideration of the effect of the above factors on the growing plant will also be necessary.

Irrigation and Biological Conditions.

As the result of supplying irrigation water and growing a crop, a food supply is provided, and climatic conditions, both in the soil and near the soil surface, altered. These new conditions may be favourable to the development of insect pests, bacterial diseases, and fungi. This is particularly the case when a part of the life-history of an insect is passed in the soil; a possible instance of this is afforded by the Pink Bollworm in Egypt.

The first serious damage by Pink Bollworm was reported in 1913, which means that the pest had been developing for some years previously, although it had not done sufficient damage to attract notice. It has been shown that the most serious uncontrolled carry-over of the Pink Bollworm is in the soil, the greatest danger being from soils on which crops not requiring much irrigation water, such as wheat, are grown. Wheat follows cotton in the rotation. Under the conditions of irrigation before the water in the Aswan Dam became available, the land which had carried wheat remained fallow from May to September. The land was dry, and the temperature to the depth of ploughing was high enough to kill the resting larvae in July. Under these conditions it is difficult to see how the soil could have been a medium of carry-over; the fallow would actually provide a gap between one cotton crop and the next. Since the Aswan Dam added to the summer water supply, the wheat stubble has been irrigated towards the end of June, and maize sown. The killing of the larvae in the soil carrying the wheat stubble has thus been prevented, and conditions suitable for the emergence of the insect established. The gap that formerly existed between cotton crops has been bridged by the irrigation of the fallow land which carried cotton the previous year. This possible instance of the alteration of the biological conditions indicates that the relationship of the use of irrigation water to insect pests and diseases is a matter to be considered in connection with the crop rotation under an irrigation scheme.

From the discussion in this paper of factors that may limit crop production under irrigation, it will be seen that problems are presented which differ from those connected with crop production under conditions of adequate rainfall. As, however, the supply of irrigation water and the method of using it can be controlled, investigation of the problems would indicate those general conditions most favourable to crop production, and the modifications necessary to deal with the particular factors of each irrigated area.