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Climate and Crops

(Ramsden Memorial Lecture)

By H. L. PENMAN

Dr. Ramsden's interest in human nutrition makes it probable that he would have welcomed an account of even the smallest of advances in solving the greatest problem in the world—growing more food. Nearly all agricultural research is seeking the sources of limitation of crop yield and ways of removing them, and during the past two decades a few groups of workers have begun an intensive study of the effect of the environment on plant growth, expecting that fuller knowledge and better understanding will lead to control. This lecture will outline part of our Rothamsted contribution to the study.

That crop growth depends on weather is accepted almost as an axiom, and nothing could seem easier than to express this dependence quantitatively by statistical correlation of yields and weather parameters. But, before starting, some definitions are needed. First, what is the yield of a crop? Choosing an important non-food crop as a difficult example, is the yield of cotton to be what reaches Manchester, or what reaches some far-distant ginnery, or all of the botanical material that is produced by the plant? For the present purpose, the last is the choice and the yield of a crop is now defined as the total dry matter produced, irrespective of its economic value. (It is noteworthy that only rarely does anyone attempt to measure the whole growth of cotton plants.) For cereals the definition is much more easily satisfied because most experimental results give both grain and straw yields, and as their ratio is near unity the botanical yield can be inferred even when only the grain yield is known. However, even with cereals the statistical approach produced very little: R. A. Fisher's analysis of the effect of weather on wheat yields was epoch-making as an innovation in statistical technique, but as a contribution to agricultural climatology it did little more than confirm folk-lore: "Drought never yet brought famine to England". Others failed, too, but fortunately a possible reason for failure is emerging. In experimental conditions, which may perhaps become the norm in British farming, good plant hygiene will control pests and diseases, and when applied to improved varieties adequately fertilised cereal yields are nearly double what they were when Fisher did his work; the incidence of pests and diseases is strongly dependent on weather and it is this second order effect that swamps the first order effect sought by Fisher. Easiest of all, yields of grass, cut for hay or silage, are true botanical yields, and for this and other reasons grass is a very good crop on which to start a growth/weather study: in the background is the knowledge that it is still the main British agricultural crop.

The second necessary definition has its problems, too. What is the weather? After deciding on a time scale, period means or totals can be picked out for the elements thought to be important (such as rainfall, temperature, sunshine, humidity, ventilation etc.) and a computer can produce a multi-correlation with yield. This direct frontal attack rarely repays the effort because the growing plant integrates the weather variables in a more complex way, but almost by chance we stumbled on a useful meteorological growth index—guided a little by a clue that emerged from the fundamental chemistry of the growth process.

Growth and energy.

Growth is the balance of two opposed processes. In *assimilation*, carbon dioxide and water are photo-synthesised to a form of carbohydrate:

$$A. \quad CO_2+H_2O+nh\nu \rightarrow (CH_2O)+O_2.$$

During growth the plant uses some of its own material as a source of energy, and the *respiration* equation is

$$R. \quad (CH_2O)+O_2 \rightarrow CO_2+H_2O+Q_s$$

with Q_s approximately 4,000 calories per gram of carbohydrate.

Then, $G = A-R$.

In passing, a minor comment is worth making. The weather that brings a large input of solar radiation will also produce high air temperatures, so that A will be strongly correlated with air temperature though, in fact, the reaction is not particularly temperature-dependent. By contrast, as an ordinary chemical reaction, R is temperature-dependent, and hence both terms in G are greatest in summer. The ratio A/R is then about four, so any statistical correlation of G and air temperature is really putting in the calendar rather than an environmental parameter.

The important clue is that $G = A-R$ is a mass and energy balance equation, and provokes a double question. Can a direct energy balance take the matter any further forward, or, if not, can the growth rate of a crop be linked with energy balances obtained for other purposes? The answer to the first part is "No", but the by-product of failure is very rewarding in clearly

exposing the scale of the challenge in crop-weather relations, and in showing where there could be significant increases in world food production. The answer to the second part is "Yes", and it will be considered in some detail against part of the answer to the first part.

Theoretical growth efficiency.

Of the incoming solar radiation that reaches a crop only about 45 per cent is photo-chemically active, and about 25 per cent is reflected: the retained useful part is about 34 per cent. Although the energetics of equations A and R give n a value near 3, the process of assimilation seems to need a value near $n = 9$, and the actual possible working efficiency is near 11 per cent. Putting in $A/R \simeq 4$, the actual theoretical efficiency of net assimilation (G) is somewhere near 8 to 10 per cent. The best achievement of very good farming is near 1 per cent—there will be evidence later—so the direct energy balance estimate fails by a factor of about ten, and thence comes the challenge: why is there a gap of such an order of magnitude, and can it be closed?

Of the reasons already known, the most important is light saturation. The theoretical efficiency can be attained in the laboratory in very feeble light, and much field and laboratory experience on crops and on single leaves, at a non-limiting constant carbon dioxide concentration, can be fitted by an equation of the form

$$G = 1/(a+b/I),$$

where G is the rate dry matter accumulates, a and b are plant constants, and I is the light intensity. At low intensities $dG/dI = 1/b$, and the biggest values of $1/b$ for field crops are in the range 4 to 7 per cent when G is expressed in energy units. The limiting value for large I is $G = 1/a$, and for many crops is almost reached when I is *c* 0·4 calories per square centimetre per minute, which is about 10 o'clock in the morning on a fine summer day. For several hours round noon all the extra light intensity is wasted.

Because of light saturation the total assimilation in a day is unlikely to be directly proportional to the total short-wave radiation received, but it is helpful to make the assumption and to set $A = \alpha R_I$ where R_I is the radiation income. The respiration, as a temperature-dependent reaction, might be set $R = f(T)$, knowing that in England $f(T)$ should have a summer value of twice that in winter. Among the components in the general energy balance of land surfaces there is one that satisfies this condition: it is the back (long wave) radiation R_B, and a second attempt at a mass/energy balance equation takes the form

$$G = \alpha R_I - \beta R_B.$$

With no immediate hope of being able to express either α or β explicitly, the best that can be done is to work with their ratio and define an energy parameter E as

$$E = \alpha R_I/\beta - R_B,$$

hoping to find that field results give a linear relationship between G and E, preferably as G/E = constant. Having introduced empiricism it must be kept within biological bounds, and a most important restriction is that E should never be negative (except slightly and briefly, to which there would be no serious biological objection). This rules out formulae that imply negative growth rates or a negative crop on the ground in mid-winter! With a long series of estimates of R_I and R_B available it wasn't difficult to find a value of α/β that satisfied the biological requirement; when done, the accumulated values of E were statistically indistinguishable (apart from a constant multiplier) from a quantity used for completely different reasons in the course of experiments. This is the *potential evaporation*, symbolised E_T, a quantity expressible either as an equivalent depth of water evaporated, or as the amount of energy used in the evaporation process.

Thus the argument based on energetics leads back to a relationship between the rate of growth and the rate of water used by the plant, an important aspect of crop climatology that needs a slightly more detailed survey in its own context.

Water supply and plant growth.

During assimilation the water is already inside the leaf, but the carbon dioxide has to get in from the outside atmosphere through very small openings in the leaf surface, called stomata. The stomata are usually open in the light, and closed in the dark, the extent of day opening depending on guard cell turgidity, which is controlled by the water content of the leaf. The main determinant of leaf water content is the amount of water around the roots, and hence the maximum opportunity for growth occurs when there is an adequate supply of water in the soil. Part of the research job, of course, is to give meanings, qualitative and quantitative, to " adequate ".

But suppose the condition is satisfied: what then? With the stomata fully open there is maximum opportunity for water

vapour to diffuse outward through the same openings. The rate of loss in these conditions is called the *potential evaporation* rate, and the valuable technical aspect is that it is a purely meteorological parameter that can be estimated from the routine weather observations taken at good meteorological stations. Briefly, the dependence on weather arises as follows: to vaporise the water, energy is needed and the source of the energy is the net radiation received in the course of radiation exchanges at the surface of the ground. As already noted, the short wave radiation retained (after reflection) is $(1-r)R_I$, where r is the reflection coefficient ($\simeq 0{\cdot}25$), and there is an outward loss of long-wave radiation, R_B, leaving a net radiation income—symbol H—of

$$H = (1-r)R_I - R_B$$

This is shared between evaporation of water, E_T (latent heat transfer) and warming of the atmosphere, Q (sensible heat transfer), and, as expenditure,

$$H = E_T + Q = E_T\,(1 + Q/E_T)$$

or

$$E = H/(1 + Q/E_T),$$

in which Q/E_T is very much more manageable than either of the components in the ratio. Omitting the complex reasoning needed to establish the dependence of H, and of Q/E_T, on the weather elements concerned, it will suffice to say that a value of E_T, the potential evaporation, can be derived from values of four elements already mentioned: temperature, sunshine, humidity and ventilation. These can be measured by setting up a weather station on the site of a field experiment, and past records can be extracted from published weather reports, for use in studies of water resources and of water needs. Much of this has been or is being done at home and overseas, and some home experience follows.

The first retrospective calculations quickly showed that our average summer total of E_T exceeds our average summer rainfall. The Ministry of Agriculture then set up a small working party to examine the relationship for the whole country and its possible farming implications. The resulting Technical Bulletin (Pearl, ed. 1954) contains several maps, including one (Fig. 1) that shows the frequency with which the summer rainfalls fall short of the potential evaporation by more than 3 inches—an arbitrary quantity chosen to represent the amount of water stored in the soil at the beginning of the summer. This is a purely climatological map, and its title needs justification. The only way of

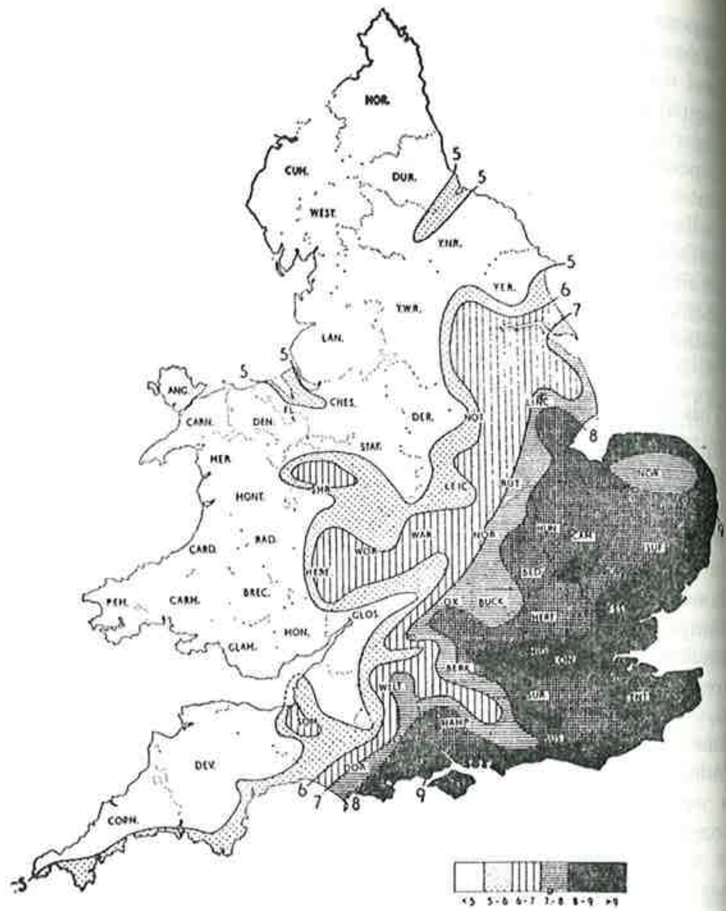

FIG. 1. Frequency of irrigation need (years in 10).

doing this is in the field, and already in 1948 we had started irrigation experiments to find out how crop growth would respond to attempts to make good part or all of the rainfall deficiency, i.e., to give a numerical value to the word " adequate " used earlier. Others gradually joined in, on fruit and on vegetables, and the whole body of field evidence, reviewed a few years ago (Natural Resources T.C. 1962) shows that averaged over all important crops the map is a very good guide to the frequency of farming benefit from irrigation. It is not entirely

coincidence that the use of irrigation as a farming technique has expanded ten- or twenty-fold since 1948: there is enough equipment on British farms now to irrigate more than 200,000 acres. Irrigation works, and it pays.

With the excellent technical return from the experiments there is an equally welcome scientific return. During the course

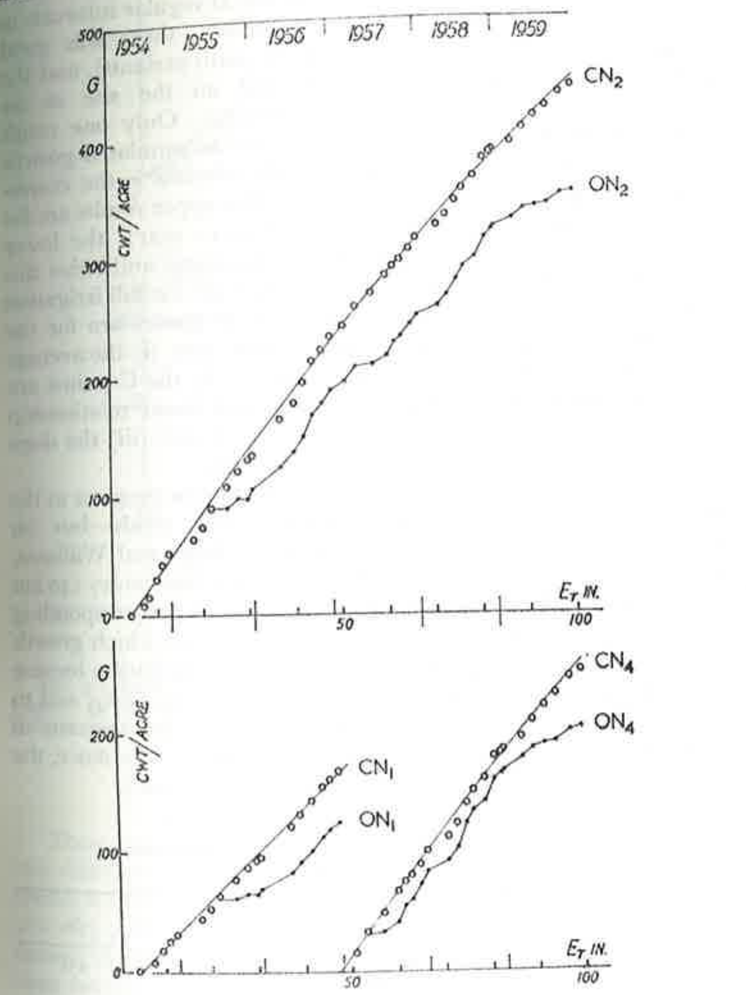

FIG. 2. Total growth (dry matter) of grass at Woburn, plotted against accumulated potential transpiration. C, Irrigated; O, Control. Nitrogen dressings in ratio 1 : 2 : 4.

of the experiment started in 1951 on our farm at Woburn, one of the experimental blocks had a ley of some sort on it for fifteen years, including a period of six years (1954–59) when a pure grass strain was maintained undisturbed until weed invasion in the sixth year demanded ploughing in and re-seeding. This seemed ideal material for a weather/growth study: there were the same plants on the same soil, cut at regular intervals in summer so that growth rates were known, there was good management, the crop was well fertilised (with variants), and the desired weather records were collected on the site as an essential part of the agronomic experiment. Only one result will be given (Fig. 2). The ordinate is the accumulated growth over five winters and six summers: the abscissa is the corresponding total of potential evaporation. The upper results are for a nitrogen fertiliser treatment repeated every year; the lower results are for half this amount (first three years) and twice this amount (second three years). The C curves are for full irrigation that kept the soil wet all the time; the O curves are for the unwatered control. The main points to note are: (i) the average gain from irrigation is about 25 per cent; (ii) the C points are well fitted by a straight line, i.e. the desired linear relationship between G and E_T is almost completely achieved; (iii) the slope of the line increases with the nitrogen dressing.

At the same time, a similar experiment was in progress at the Grassland Research Institute, Hurley, and yields—but no weather records—were published recently (Stiles and Williams, 1965). Using the weather records from Kew Observatory (40 km to the east) I have calculated E_T to give the corresponding diagram (Fig. 3, upper), and a variant (lower) in which growth (in energy units) is plotted against short-wave radiation income (R_I). Again there is the nearly constant value of G/E_T, and to show the degree of consistency, Table 1 gives the two sets of values at the varied level of nitrogen treatment. (By chance, the amount and form of the fertiliser used were the same.)

TABLE 1

Mean growth rate per unit increment in potential transpiration
100 kg ha^{-1} per 1 cm transpiration

Site	*Sward*	N_0	N_1	N_2	N_3
Woburn	Cocksfoot	—	1·9	2·4	2·8
Hurley	Rye-grass/Clover	1·8	2·0	2·4	3·0

N_1 19; N_2 38; N_3 76 kg ha^{-1} N per cut.

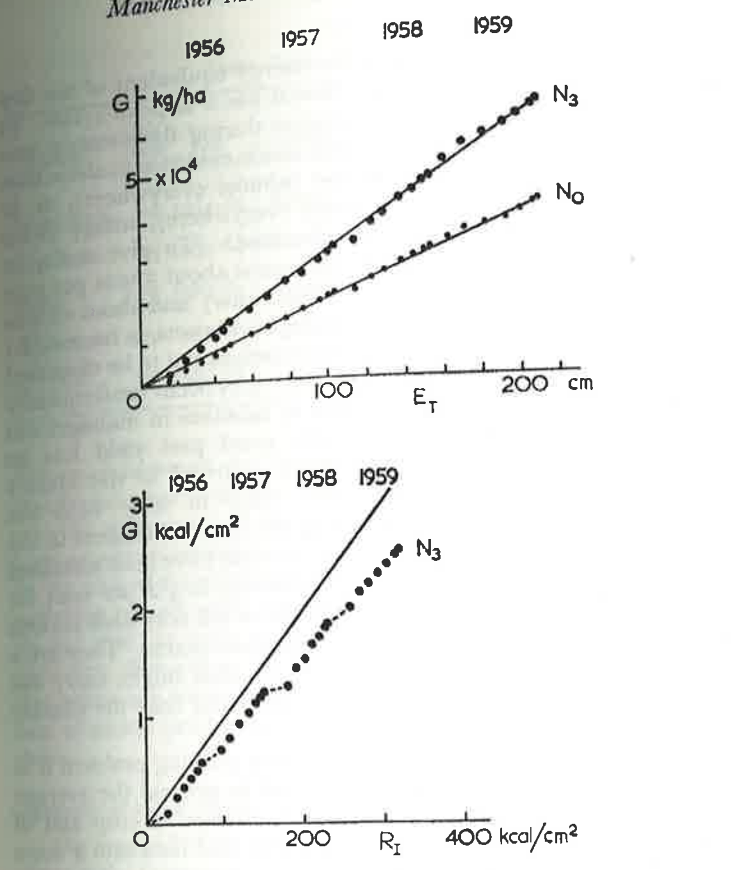

FIG. 3. Total growth of rye-grass/white clover at Hurley on irrigated plots. Upper: yield as dry matter. N_0, no nitrogen dressing; $N_3 = N_4$ of Fig. 2. Note changed units. Lower: yield as energy equivalent.

(Yields from Stiles and Williams, 1965.)

These two field experiments have given the same result on two different species of grass (other work at Hurley shows the species is unimportant), and obviously the potential transpiration is a very good growth index when water supply is not a limiting factor. A simple hypothesis to specify when soil water supply does become limiting was formulated and successfully tested: omitting any discussion here, it is more useful to maintain the thread of the discourse by considering the lower part of Figure 3.

The efficiency of good farming.

The ordinate of Figure 3 is the energy equivalent of the dry matter in the crop, and the line drawn has a slope of 1/100. In all four years the efficiency of fixation during the summer was close to 1 per cent, and there is now much evidence to show that in experiments on other crops too (almost everywhere), or in good commercial farming (*not* found everywhere), energy yields of this size—or better—can be obtained. (To give scale, in terms of crop yields, in England this means about 5 tons per acre of hay, or of cereals, as total grain and straw; and about 20 tons per acre of potatoes, or of sugar beet, tops and roots, as harvested.) Within the linear trends there are fluctuations not to be dismissed as " experimental error " and forgotten: they occur too frequently in field results to be all attributable to mistakes in management or recording, and the exceptionally good plot yield has an importance of its own. One of these occurred in the Hurley experiment, when over twenty-nine days in May 1958 the average efficiency of fixation was 1·54 per cent: elsewhere in the world fixation efficiencies of 2 and 3 per cent have been sustained over a few days (one of the biggest known is 4·2 per cent for bulrush millet in Australia), and it is fair to ask why such periods cannot be lengthened, for more crops in more places. They are a source of encouragement in the research that might carry the already very good a little nearer the potential that the climate will allow.

On a broader front, however, the more pressing problem is to bring the average nearer to the best, and in general the average is only about one-half of the good. A change of crop and of climate will illustrate this particular point, and lead into a more extensive survey of crop climatology.

The efficiency of cotton growing.

Cotton is a crop with a limited geographical range and there is little to be gained by using efficiencies of fixation of solar radiation for first comparisons: the variation in the denominator R_I, is small compared with the uncertainties in the yields. Table 2 shows yields of lint for two groups of countries. On the left are some of the best average national yields; on the right, with two sets of figures, are yields from African states where there is research on cotton growing—one set giving the national average, the other giving the best from an experiment. (Information kindly supplied by the Cotton Research Corporation.) Two contrasts are noteworthy. On the right there is a measure of the

TABLE 2

Cotton Yields: Lint: 100 *kg ha*$^{-1}$

Country	*Yield Mean*	*Year*	*Country*	*Yield Mean*	*Year*	*Yield Expt.*	*Year*
Guatemala	7·2	1964–65	Kenya	0·6	1963–64	8 to 9*	1964
Honduras	8·3	1963–64	Sudan	3·6	1962–63	10·4	1965–66
Israel	12·2	1964–65	Tanzania	2·7	1964–65	8·4	1966
Nicaragua	9·2	1964–65	Uganda	0·9	1964–65	7·6	1966–67
U.S.S.R.	7·3	1964–65					

* est. from seed cotton yield.

difference between the average grower and the farm manager who knows what to do and has the equipment to do it. Comparing extreme right and left, the best from experiment is not different from average commercial achievement in other parts of the world. At the sites of the experiments in Kenya and Uganda there were radiation records and, *assuming the total botanical yield was nine times the lint yield*, at both places the efficiency of fixation was near 34×10^{-4}. Subject to the uncertainty in the assumption, it seems that there are important non-climatic factors limiting even the best of cotton production in Africa, possibly by a factor of about three.

Efficiency of world farming.

On a world scale this new unit of efficiency—10^{-4}—becomes alarmingly important. The annual total of incoming radiation is known approximately for the whole world (Budyko, 1955) and the range over the areas in which there is any important agriculture is about three to one. Average crop yields for nearly all major crops for nearly all countries are known (F.A.O. 1965), and, although the staple crop varies, all countries grow several species of cereal crops. For these it is fairly safe to double the published grain yield to get the total botanical yield and, converting at 4,000 calories per gram, to express this yield as an efficiency of energy fixation. This has been done (Penman, 1968), excluding rice, and in spite of the great uncertainties in both of the primary sources of data, a remarkably consistent world picture emerges, as a measure of farming efficiency with the main climatic variable eliminated. Around the North Sea in the industrial countries of

N.W. Europe the efficiency of average farming is near 35×10^{-4}; in the Iberian peninsula it is 7×10^{-4}; in the United States and Canada it is just under 20×10^{-4}; in the Caribbean it is about 6×10^{-4}; in South America it is about 8×10^{-4}; in tropical Africa and Asia it is about 3×10^{-4}. This last figure should be doubled to allow for the fact that it is possible to grow two crops a year, but, even so, this still leaves a factor of five or six for the ratio of farming output as an industry and farming output as a subsistence activity.

One of the reasons often given for small tropical yields is lack of water, but when rice yields are compared with those of rain-watered cereals many are no better, and in some countries they are slightly worse. There are, however, places where the reason is valid (notably Spain and Portugal, where the efficiency of rice production is near 35×10^{-4}), and in these irrigation will greatly increase crop yields.

Conclusion.

This survey of crop climatology has revealed several gaps, and working backwards, the first (factor of about five) is the gap between average achievement in under-developed countries and that in developed countries. Those with the experience to make a judgment can see no technical reason why the achievements should not be equal: the obstacles seem to be chiefly social, religious and economic. The second gap, found everywhere, is that between the average and the best (factor of about two). The British average, near 35×10^{-4}, represents a range of " best " of about 70×10^{-4} upward, reaching beyond 1 per cent by the really good, or in experiments. Then there is the gap between the best and the potential (factor of about ten), which will need some skilful fundamental research on how plants grow if it is to be made narrower. There are already a few places in the world where there is work of this kind, and new studies of the climatic aspects of plant productivity form an important part of the International Biological Programme.

When it decides that it really wants to do so, the world can feed itself adequately, probably from a smaller area than is now used. Nowhere is there anything like full exploitation of the primary energy income, and in those countries that come closest to doing so, there is still much helpful work to be done by the plant breeder, the plant pathologist, the engineer and the soil chemist. Many countries suffer because an energy income that is too great imposes a water requirement that cannot be satisfied

by rainfall, and even where the annual average amount is adequate in total, seasonal distribution and year to year variations may greatly limit crop production. Assuming that the water can be found, transported and used at not too prohibitive a cost, irrigation can remedy deficiencies of rainfall but cannot remedy non-climatic deficiencies arising from bad management of poor plant material on neglected or ill-treated soils. Good agriculture needs good farming, and only the best farming can exploit irrigation fully.

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