Footnote to Freedom from Want

A Quantitative Appraisal of the Food and Population Problem

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IN THE SHADOW of World War II, Franklin D. Roosevelt, then president of the United States, proposed world-wide "Freedom from Want" as one of the four major aims of the peace that was to follow that global conflict.

This bold idea of a hunger-free world stirred the imaginations of men everywhere, and focused their attentions on the facts of life under which humanity may or may not exist in comfort. It awakened a wider consciousness that an overcrowded world, even in peace, cannot live comfortably by personal and national freedoms alone. Above all things, people must eat, and they must eat enough to sustain them not only for the tasks of daily life but also for the enjoyment of being alive.

Freedom from want in the Rooseveltian sense was to replace the long-standing condition whereunder more than half the world's population subsists at a level of nutrition below the standard set by nutritionists as the minimum for effective living. The worst of this situation is that it is self-accelerating. Under the drive of the human instinct for procreation the world's birth rate—with negligible exceptions—has been and still is exceeding the world's death rate, while the physical means for agricultural food production remain fixed by the area and configuration of the earth's land mass.

This is the setup which demographers and social-scientists describe as "pressure of population on the soil": a definitely limited area of arable land is called on to support more and more people. The consequence is that the per capita share of food produced on this land becomes smaller and smaller, and for large segments of the world's population the pinch of hunger is becoming more and more oppressive.

Unlike other schemes for world betterment, the Rooseveltian idea was destined to have behind it a world-wide organization composed not of academic humanitarians, but of scores of the world's governments who in 1945 founded the

United Nations as an agency that would bring peace and plenty to men everywhere. The first objective of this agency was to provide an apparatus for restraining war-minded nations from aggression on their neighbors; in case of aggression the other nations would throw their weight against the aggressor. With world-wide peace thus assured, the combined energies of all nations could be directed to promoting their general welfare—for which, as a prime condition, there must be a general rise in per capita food production, particularly in the agriculturally deficient regions.

FAO, Its Problem and Its Hope

To implement its program of freedom from want the UN established a subsidiary called the Food and Agriculture Organization (FAO), and assigned it the task of improving the agricultures of backward nations. In effect, the task of FAO is to bring *all* the world's agriculture up to the standard of efficiency set by "the best farming methods known to science." Now well past its first decade, FAO has a number of worthwhile undertakings to its credit and has won respect by producing significant improvements in areas where it has had time to show what it has to offer.

The problem that confronts FAO is, essentially, to increase food production at a rate faster than the increase of the world's population.

At the outset (1946–47), a symposium was held under the auspices of the American Association for the Advancement of Science to appraise the situation by equating two groups of factors. On the one side is the known area of land now under cultivation, plus all the presently unused land (estimated at 1.3 billion acres) that could be brought under the plow. On the other side are the world's population at the starting date, its probable future rate of increase, and the minimum per capita food requirement for normal health and vigor. The equating coefficient is then a presumed acre-yield of food if the available land were farmed according to the best methods known to experts in the world's most advanced agricultural colleges and experiment stations. From these data it was calculated that by 1960 the existing deficiencies would be made up, and the world would be producing just enough food to give everyone at least the equivalent of an adequate diet. Food production and food consumption would then be in satisfactory balance. But 1960 is almost upon us, and on the whole the world is no better fed than in 1946.

No fault need be imputed to the calculated date for the world to enjoy freedom from want; this date was derived from the best data then available. If the data had been different a different date would have resulted. *Whatever the date,* this would be the situation:

By putting every suitable acre of soil into cultivation, and by calling up every known resource of agricultural science under the direction of the world's ablest agriculturists, it would be possible under the assumed conditions to establish a tolerable equilibrium between supply and demand for food. However, the equilibrium thus attained could only be temporary; having thrown everything they had into the effort, the agriculturists of the time would be left with no unused reserves through which a single additional ear of corn might be produced. Meanwhile, world population would keep right on increasing according to schedule. With an ever-growing number of mouths to be fed, the momentary state of equilibrium would fade, and the recession into Malthusianism would be resumed.

In the face of this dismal outlook the chiefs of FAO were left with only an undefined hope that new reservoirs of knowledge to be discovered might enable the world's agriculturists to raise the presently-presumed maximum possible acre-yields and thus keep food supply ahead of the birth rate. Farm experts of today are indeed using better methods than they were 20 years ago, and every passing year brings significant improvement. But these yearly accretions of knowledge accumulate at a pitifully slow rate in comparison with the swift increase in the number of mouths to be fed.

Here we come to the point. The question may be put: Does there exist a tangible prospect that FAO's vague hope for salvation through science may be transformed into a fixed assurance, to which can be assigned a definite form and a definite dimension? The purpose of this article is to answer that question by reference to certain basic facts of plant life and growth which contemporary plant scientists as a body—plant physiologists, geneticists, soil scientists, and agronomists—have been overlooking.

Plant growth and yield depend on the joint action of certain natural forces or factors. These co-acting factors are outer and inner. The inner factor is a living force in the germplasm of the plant; it becomes active only when stimulated by the outer factors. These outer factors are split into two groups: physical agencies such as the light and warmth of the sun which are uncontrollable by man (except in greenhouses), and certain chemical agencies that reside in the soil and in the air and include nitrogen, phosphorus, potassium, and other common ingredients of fertilizer, carbon dioxide, and water. Each of these chemical agencies is endowed by nature with its own special attributes, and each exercises an amplifying influence or, alternatively, a restraining influence on the growth-promoting actions of all the others. It is most enlightening to integrate this complexus of factors, and to see the unity that pervades the apparent diversity.

Two Controlling Natural Laws

It may be stated in advance that this process of integration of growth factors winds up by disclosing that the food-and-population problem, insofar as it depends on agriculture, is defined, controlled, and decided by two basic entities of natural law in the world of plants. These controlling entities hold condominion over all the quantitative aspects of plant growth everywhere. They are (1) the law of diminishing increments of yield, and (2) the inverse yield-nitrogen law. It is not too much to say that those who do not understand the interlocking functions of these two principles can have little or no real comprehension of either the natures of plants or of their built-in capacities for supplying food for the animal world. These functions will be explained as fully as limited space will permit.

Take first the law of diminishing increments of yield. This member of the condominion that controls the quantitative aspects of plant growth is an expression of the very inconvenient fact that it is impossible to produce an unlimited amount of vegetable substance on a limited area of soil in one cycle of plant growth (from seed to seed again). Yet nature allows this harsh law to operate within a certain margin of liberality. A soil that may be described as "poor" will give a better yield if it is supplied with one unit of a certain mixed fertilizer. If instead of one, the soil has been furnished with two units of the fertilizer, the yield will be better, but the increase from the second unit will not equal that produced by the first; a third unit will produce less than the second, and so on. As the amount of fertilizer is indefinitely increased the yield will increase by always diminishing increments until a point is reached beyond which more fertilizer will not induce the plants to increase their growth.

Thus, no matter how "rich" the soil is made, and no matter how well the crop is tended, nature has imposed an absolute limit on agricultural food production from a fixed area of land. At the limit, the crop will have given its perultimate (maximum possible) yield because it has been grown on a "perfertile" (richest possible) soil.

However, without in the least departing from the law of diminishing increments, nature has contrived that the other member of the condominion—the inverse yield-nitrogen law (which is concerned only with the inner factors of plant growth and which will be described farther on)—may intervene to provide a limited loophole through the barrier set up by its co-acting law. This means of partially by-passing the law of diminishing increments lies in the fact that different kinds of plants have inherently different yielding abilities; a certain variety of wheat, for example, will give more bushels of grain per acre than another kind of wheat when both are planted on the same uniformly-fertile soil. Here, both kinds of wheat are under the same nutrition pressure, exerted on their roots by the same kinds and concentrations of chemical agents in the soil. The sole difference is that nature has provided the higher-yielding wheat with a greater inbred metabolic energy for utilizing the materials placed equally at the disposal of both. The same situation applies to all other food crops, whether corn, sugar beets, soybeans, potatoes, cabbages, or whatnot.

It comes down to this: The productivities of food crops are primarily functions of the inner natures of the plants themselves, and in a very important sense are independent of the soil. Nature uses the law of diminishing increments to establish, for all kinds of plants without known exception, a fixed limit on the amounts of fertilizer that can be usefully employed on one acre of any soil, and uses the inverse yield-nitrogen law to allow one kind of plant to produce more vegetable substance than another from the same original amount of fertilizer. The law of diminishing increments is not deprived of its jurisdiction; the plants do the best they can, each according to its kind, with what is impartially given to all.

Two Crucial Questions

Thus far, the discussion has been about the general, or qualitative, aspects of these two entities of natural law in the world of plants. To give the picture definite form and dimensions it is next in order to fill in the quantitative details. On the one hand we have the fact that by use of sufficient fertilizer and the other necessary outer factors, we can effectively enrich the soil up to a certain point, but no farther. On the other hand we are free to plant crops which can make the best possible use of this amount of soil fertility. With this set-up we may proceed to look for answers to the following questions:

(I) What, in terms of pounds per acre, is the quantitative composition of the maximum useful amount of a "complete" mixed fertilizer allowed by the law of diminishing increments?

(II) And what, in terms of bushels or tons of dry vegetable substance, are the acre-yields of the crop plants which nature has endowed with the highest attainable energy for growth?

Old irrigation system in Egypt. Men stand in the water to operate a water-lifting device known as the "shaduf"

Verified answers to both these questions have already been found and have been known for many years. Yet contemporary plant scientists are neglecting a situation that could lead them directly, and in the shortest time, to full control of the earth's limited ability to produce agricultural food within the norms laid out in the law of diminishing increments and the inverse yield-nitrogen law.

The Historical Background

In exploring these two questions we begin again with the law of diminishing increments. This member of the condominion that rules and limits the fruitfulness of the earth was ushered into formal scientific thought in the 1820's by the English economist John Mill. Taking wheat as his example, Mill showed that a farmer, by applying a certain intensity of cultivation in preparation of the land and use of manure, might obtain a "quarter" of grain, but if he doubled this intensity he would not obtain two quarters; if he tripled the intensity the increase of yield would be still less, and so on until there would be no further increase. Mill did not go into quantitative details, but his idea was seized upon by the "political economists" of the time who named it the "law of diminishing returns" and extended its scope to all industrial and commercial situations involving cost-price-profit relations.

Liebig

The first step toward evaluating the quantitative relation between crops and fertilizers was taken in the 1840's by the famous German chemist Liebig, who is regarded as the father of agricultural chemistry. He proved that growth and yield of plants depend on certain chemical substances in the soil such as nitrogen, phosphate, and potash. He experimented with soils containing different quantities and proportions of these plant nutrients, and evolved a theory that was to rule the thoughts of agriculturists for 70 years. This theory, called the "law of the minimum," holds that the yield of crops is the resultant of all the factors of plant growth, acting jointly and simultaneously; if even one of these factors is missing there will be no yield; further, the quantity of yield is dependent on the relative proportions of the factors in the nutritive mixture, and will be restrained by that component which is present in the smallest proportion (or is "in the minimum"). The yield can then be raised (according to Liebig) only by increasing the quantity of this minimum factor until some other factor takes its place as the minimum one. By successively increasing the successive minimum factors the yield may be increased indefinitely and a nearly unlimited amount of vegetable substance should be obtainable from a very small area of soil, "even a flower pot!"

The agriculturists of Liebig's time reacted enthusiastically to his law of the minimum. The agricultural implications of Mill's law of diminishing returns fell into disrepute, and the way seemed open to a vast increase of food production without a material increase of the area of arable land. Laboratories for soil analysis were established so that farmers might have guidance for adjusting the plant-food content of their soils. The Englishman Lewes established the world's first factory for manufacturing commercial fertilizer and he founded, at Rothamsted, the world's first agricultural experiment station. Numerous similar institutions were set up in the principal countries of the earth.

Naturally, the growing use of fertilizers was generally reflected in an increase of average production, but after a time it began to appear that there was no great magic in the law of the minimum. Though the crops grew better than before, they continued to display the old tendency to respond by diminishing increments, just as Mill said. But for a long time the agricultural scientists refused to abandon their trust in Liebig's law.

To account for their disappointment they thought there was some fault in their technique. It was well known that plant growth depends on a great complex of agencies; perhaps among these is one or more that are still unknown and are persistently remaining in the minimum. Liebig's successors, therefore, embarked on a search for the missing factor or factors, and as time went on they made some encouraging finds; to such previously known essential nutrients as nitrogen, phosphate, and potash were added magnesium, sodium, sulfur, manganese, molybdenum, copper, and zinc, which are just as essential as the "big three" but are needed in much smaller quantities.

But all along, the over-all situation remained in the firm grip of the law of diminishing increments. Obviously, Mill's law is here to stay, and the situation is lodged in one or the other of two possibilities: Either there is an unlimited number of factors of plant growth still to be discovered, in which case it will be possible to produce, in the Liebigian sense, an unlimited amount of vegetable substance from a limited area of soil; or, the number of essential factors is limited to those already known, and possibly a very few others. In the latter case Mill's law will continue to hold in full rigor when all factors are brought up to their maximum individual and collective efficiencies.

Since only the future can decide whether there are any essential factors still unknown, this discussion will proceed on the assumption that the human race at this moment is in possession of all the physical and chemical means for food production it will ever have. If so, it is of supreme importance to have an appropriate experimental procedure for determining (1) the largest possible quantity of yield that each kind of crop can be made to give in any event, and (2) the exact quantity of each of the known factors of plant growth needed to make the crop reach its limit.

Mitscherlich

The needed "appropriate experimental procedure" was contrived 50 years ago by Eilhard Alfred Mitscherlich, a professor of agriculture at the University of Königsberg. At that time (1909) the Liebigians were still making field experiments in the hope of overcoming their difficulties with the law of the minimum. Mitscherlich reasoned that the only way for effective study of the properties of a growth factor would be to use it as a single variable in a soil that was abundantly provided beforehand with all other known essential factors. This single variable could be increased by stages but would always be the only one in the minimum position. For his basic culture medium, Mitscherlich used a sterile quartz sand free from all soluble matter that could be absorbed by plant roots. He mixed this barren sand with adequate quantities of all factors of plant growth except the one (potash for example) to be studied. On a known area of this otherwise perfect soil he planted a known number of seeds of any kind of crop. There being no potash in the soil there was no yield; when a small "dose" of potash was added, there was some yield, and more could be obtained with successively larger doses of potash. The results could be shown in diagrams, with yields plotted against doses of potash. It could then be seen whether the increasing yields traced a straight line (Liebig) or a curve that was approaching a determinable limit (Mill).

Beginning in 1909 and continuing until shortly before his death in 1953 at age 83, Mitscherlich executed thousands of such experiments, mostly with nitrogen, phosphate, and potash and their combinations such as are now used in commercial fertilizers. He found that no matter what kind of crop he was studying, or what growth factor he was using, the normal increases of yield conformed accurately to a single type of curve that could be represented by the differential equation

$$dy/dx = (A - y)\ c$$

which on integration becomes

$$\log\ (A - y) = \log A - cx$$

The four parameters of this equation are: x, the increment of growth factor used at a particular stage in the process of enriching the soil; y, the increment of yield resulting from that much of that factor; A, the maximum possible yield that could be obtained if x were indefinitely increased; and c, a factor of proportionality that represents the specific nutrition effect of the growth factor increment x.

The essence of Mitscherlich's accomplishment lies in his demonstration that the law of diminishing increments of yield in agriculture applies to every kind of crop and to every known factor of plant growth whether physical or chemical, and that every such factor is characterized by its specific quantitative effect (c) on the growth and yield of plants. To general plant science he has bequeathed his "law of physiologic relations," now known as Mitscherlich's "effect law," which he has stated in the following terms: "Within every factor of plant growth there resides a perfectly definite effect factor that is constant under all circumstances of soil, of climate, and of cultural conditions, and is independent of the nature of the plant."

The accepted values of the constants c of the three principal ingredients of fertilizers in the Mitscherlich equation are: for nitrogen (N), 0.122; for potash (K_2O), 0.40; for phosphate (P_2O_5), 0.60. These constants define the slopes of the yield curves corresponding to the specific effects of these plant nutrients.

Baule

Nine years after Mitscherlich published his discovery, which is surely the most important contribution that the twentieth century has yet made to plant science, his yield equation came to the attention of B. Baule, a professor of mathematics at the University of Gottingen. Baule wrote it in the form:

$$\log\ (100 - y) = \log 100 - kx$$

wherein instead of the symbol A the numeral 100 is used to represent 100% of the maximum possible yield of any kind of crop, and k is a generalized coefficient in which are pooled all the functions of the various Mitscherlich constants c for the individual growth factors.

Baule made no direct addition to Mitscherlich's fundamental discovery, but his revamping of Mitscherlich's equation has been of great help in illuminating and extending the theoretical and practical consequences of his law of yield, by which it has become possible to arrive at a definitive statement of the ultimate ability of the soil to produce food.

The difference between Baule's and Mitscherlich's equations lies in the choice of units in which to measure the independent variable x. Mitscherlich measured his experimental quantities of plant nutrients—whether nitrogen, phosphate, potash, lime, magnesia, sulfur, etc.—in DZ/hectare, which in Anglo-American numeration corresponds to lb./acre. This makes calculations by his equation laborious and time-consuming. Baule took as the unit of a factor of plant growth that amount of it which would be sufficient to produce half (50%) of the total yield which that factor could produce if it were increased up to the limit permitted by the law of diminishing increments. While the first such unit evokes 50% of the total response, a second similar unit will add only half as much (25%); a third unit adds half as much (12.5%) as the second one, a fourth half as much (6.25%) as the third, and so on until a tenth unit will bring the total yield to 99.99% of the ultimate possibility. The capability of the crop to give yield under the action of that factor will by then have been virtually exhausted. Or, as the agrobiologists say, it has spent the whole of its "quantity of life." Here Baule has employed what has been called the "rule of halved increments" used by physical chemists to evaluate irreversible monomolecular reactions in which an isolated source of potential energy is dissipated or down-graded as it approaches exhaustion.

Finally, to bring this bit of agricultural history to a close, it remains to account for Baule's general coefficient k that replaces Mitscherlich's individual constants c, and to show how Baule's x is determined. Since in all systems that come under the rule of halved increments the independent variable is increasing by equal units, the x in Baule's equation is 1 or a multiple of 1. Suppose that in a given case x = 1 and will produce half (50%) of the expectable total response. Then

$$\log(100 - y) = \log 100 - kx$$
$$1.69897 = 2.00000 - k$$
$$k = 0.30103,$$

which is the logarithm of 2.

As for the value of Baule's x pertaining to an individual growth factor, this is determined by the formula 0.30103/c, in which c is the corresponding Mitscherlich constant for that factor. A Baule unit of nitrogen (N) is therefore 223; of potash (K_2O), 76; and of phosphate (P_2O_5), 45 lb./acre. So the whole of Mill's concept of the law of diminishing returns in agriculture, which was crystallized by Mitscherlich in his law of yield, now assumes its definitive form as the rule of halved increments in Baule's equation:

$$\log(100 - y) = \log 100 - 0.301x$$

A typical Mitscherlich-Baule yield curve is shown in Fig. 1.

Quantitative Agrobiology

This simple equation, which can easily be handled by a person able to use logarithms, has become the basis of a new mathematical discipline within the general science of plants. It is called "quantitative agrobiology," and includes within its province every dynamic relation between quantity of plant growth and quantities of the external factors required for producing that growth. In effect, by using the Mitscherlich-Baule theorem in conjunction with the inverse yield-nitrogen law (to be described) the quantitative agrobiologists have defined the ultimate limits of plant growth. They have found these limits to be far above the best that traditional agriculture has been able to achieve or even to imagine, and they have shown how the ordinary factors of crop yield may be managed so as to approximate these superior limits. In so doing they have opened the possibility of such vastly increased production of agricultural food from the world's existing area of arable land that a comfortable balance between population and food supply would be assured for hundreds of years.

The quantitative agrobiologists have worked themselves into this commanding position by finding the answers to the two crucial questions raised in the introduction to this article. These questions are:

(I) What, in terms of pounds per acre, is the quantitative composition of the maximum useful amount of a "complete" mixed fertilizer allowed by the law of diminishing increments?

(II) And what, in terms of bushels or tons of dry vegetable substances, are the maximum possible acre-yields of the crop plants which nature has endowed with the greatest energy for growth?

Answers to both questions may be inferred from the schematic diagram of Fig. 2.

In the lower half of this diagram are three continuous Baule yield-curves. The lowest of these curves, A, represents a kind of crop that is genetically characterized by a relatively small yielding ability; the best it can do under the most favorable conditions is to give a maximum yield of 60 scale-units. The curve next above, B, represents a more copious yielder, which under the same soil conditions can attain a maximum yield of 80 units. Still better is crop C, which is able to give a maximum of 100 units.

All three crops grew on plots of the same uniform soil that contained full quantities of all essential nutrients except nitrogen; the latter was supplied in successively increased amounts

Fig. 1. A typical Mitscherlich-Baule yield curve

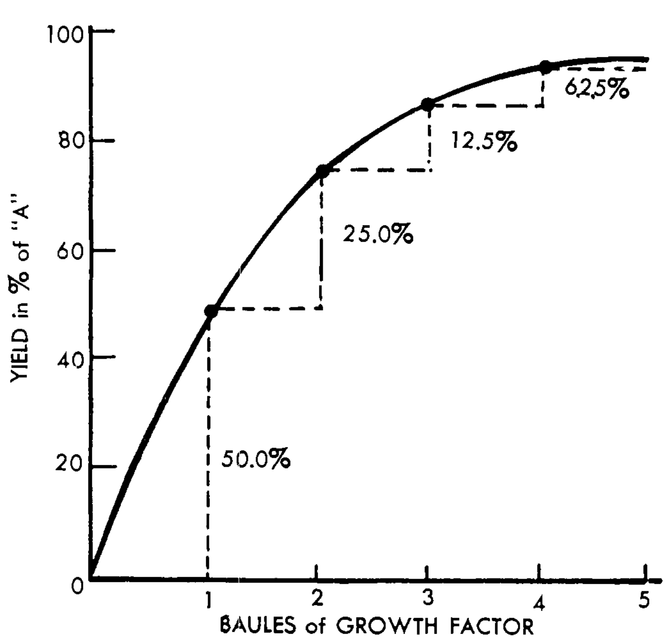
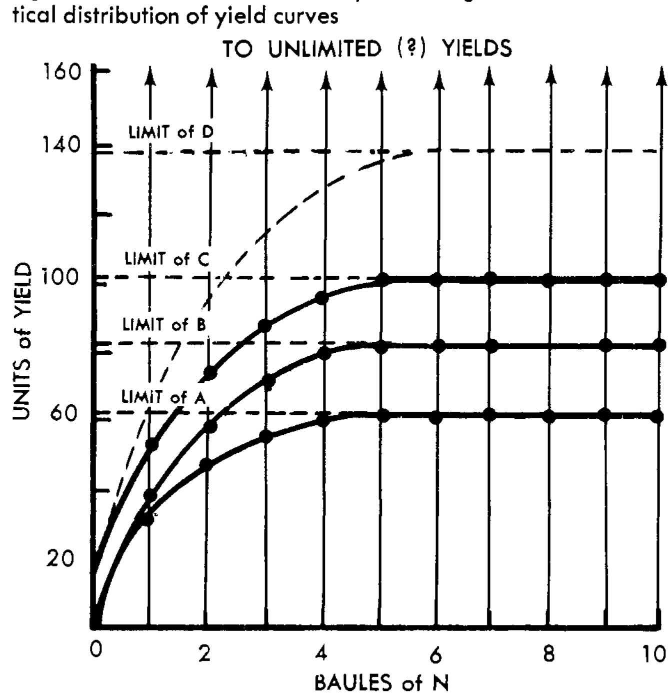


Fig. 2. Influence of the inverse-yield nitrogen law on the vertical distribution of yield curves



up to a total of 10 baules (2,230 lb./acre) of this growth factor. At the first stage, with one baule of N, crop A yielded 30 units, B 40 units, C 50 units. With two baules of N the yields were 45, 60, and 75 units, and at every succeeding stage the responses were in the same ratio to the end, with A coming out with a perultimate (maximum possible) yield of 60 units, B with 80, and C with 100 units.

We are here confronted with two inseparably connected facts. First, when different kinds of plants are given access to the same combination of nutrients stored in a perfertile (completely fertilized) soil, they may give very different yields.

The other side of this proposition is that the combination of nutrients in a perfertile soil containing 10 baules of each essential nutrient will completely meet the needs of all kinds of plants, regardless of the different yielding abilities of these plants. Lest this statement be misunderstood it will be restated in another form: For full development of any kind of crop, whether a high yielder or a low yielder, the soil must contain 10 baules of every plant nutrient. This is what is meant by Mitscherlich's assertion that the effect factor of a growth factor is independent of the nature of the plant. All come under the same physicochemical nutrition pressure, although they may respond with different yields.

Two Precepts for Maximum Food Production

From the foregoing considerations quantitative agrobiology lays down two simple precepts for attaining the utmost limit of food production from one acre of land:

(I) The soil should in every case be stocked with 10 baules of every essential plant nutrient, which, per acre, will require 2,230 lb. of nitrogen (N); 450 lb. of phosphate (P_2O_5); 760 lb. of potash (K_2O); 14 lb. of magnesia (MgO); and 4.5 lb. of sulfur (S); to these must be added abundance of water and small amounts of the "minor" nutrients if these are found to be deficient.

(II) Only those kinds of crops that have been proved to possess the highest attainable quantity of life or energy for growth should be planted.

Point II above raises the question of what is or may be the largest possible yield attainable by any kind of crop plant, and how such plants may be identified or created by systematic plant breeding.

The Inverse Yield-Nitrogen Law

This brings us abreast of the inverse yield-nitrogen law, mentioned previously as one of the two major natural laws that control the fruitfulness of the earth. The author has a claim on credit for discovery of the universality of this law of the plant world back in 1928. No great genius was required for this discovery; it involved nothing harder than correlating, where no one had thought of looking for such correlations, crop analyses and crop yields from the data of hundreds of field tests officially published by dozens of experiment stations.

For an example refer to Table I, in which are compiled the results of a four-year field test with five hybrid corns reported from the Illinois Experiment Station at Urbana, Ill. Passing downward from the top of the Table, note that as the relative yields of the varieties decreased in each of the four seasons, the nitrogen percentages increased. Or, passing from the bottom to the top of the table, as the nitrogen percentages decrease, the relative yields increase.

From such observations the inverse yield-nitrogen law was formulated thus: "Of two or more different kinds of plants growing simultaneously on the same normal soil, that one with the smallest percentage of nitrogen in its dry substance will be found giving the largest acre-yield."

That is to say, yield is always inversely proportional to percentage of nitrogen in the crop. After nearly 30 years in pursuit of this correlation the author has yet to find a sustainable exception. And now arises a third crucial question:

(III) Since in all nature every dynamic system must approach some sort of end, toward what ends do in-

Table I. Relation Between Yields of Nitrogen (Protein) in Five Varieties of Corn

Varieties	Dry Substance (lb./acre)	Nitrogen in D.S. (As protein, %)	× (As N, %)	N in Crop (lb./acre)	Lbs. D.S. per lb. N
		1950			
USH 13	9,800	9.7	1.55	151.9	64.5
H-PC	9,000	10.2	1.63	146.7	62.0
IH-P	6,800	12.6	2.01	136.1	49.7
		1951			
USH 13	12,000	9.0	1.44	172.8	69.4
H-PC	10,600	9.8	1.57	166.4	63.7
IH-P	8,800	11.6	1.86	163.7	53.7
		1952			
USH 13	11,200	9.4	1.50	168.0	66.6
H-PC	10,600	9.7	1.55	164.8	64.3
H-PD	10,200	10.5	1.68	171.3	59.5
H-PE	8,400	11.7	1.87	157.1	53.4
IH-P	6,600	13.0	2.08	137.3	48.1
		1953			
USH 13	10,600	9.7	1.55	164.3	64.5
H-PC	8,600	9.8	1.57	135.0	63.6
H-PD	8,000	10.3	1.65	132.0	60.6
IH-P	7,800	11.8	1.89	147.4	53.1

Averages

Varieties	% N	Lb. D.S. per lb. N	Average Yield, Lb.	Differences
USH 13	1.52	66.3	10,900	–
H-PC	1.58	63.9	9,700	1,200
H-PD	1.66	60.0	9,100	600
H-PE	1.87	53.8	8,400	700
IH-P	1.95	51.1	7,500	900
			Over-all difference	3,400

Source: (Illinois Agricultural Experiment Station, 1950–1953).

creases or decreases of yield with decrease or increase of nitrogen percentage approach?

Two Asymptotes of Quantitative Plant Life

Refer again to Fig. 2. Above curve C is a broken Baule curve D to represent any kind of crop with a smaller nitrogen percentage than crop C and therefore a greater ability to produce vegetable dry substance. Beyond D there is still empty space; the lengthened ordinates tipped with arrows suggest that as nitrogen percentage in the plants is further decreased, the quantity of yield from one acre of perfertile soil might be indefinitely increased simply by breeding crop plants with lower and lower nitrogen percentages.

Attention may now shift to the curve of Fig. 3, in which pounds of dry vegetable substance are plotted as functions of percentage of nitrogen in the dry substance. At about the middle of the curve stands the white potato, a major food crop that has a relatively small percentage of nitrogen and therefore relatively large quantity of life. From this point downward to the left the curve passes successively through sugar beet, rice, wheat, the five Illinois hybrid corns previously mentioned, clover, and two kinds of soybeans. In this direction nitrogen percentage increases, and yield of dry substance decreases as the curve flattens and approaches a horizontal asymptote. A crop standing at the point where curve and horizontal asymptote seem to merge would contain the highest percentage of nitrogen that will ever be found in any green plant, and its yield of dry substance would be smaller than that of any crop standing above it on the curve. Here photosynthesis per growth cycle is at its lowest quantitative intensity.

In the reverse direction upward, this system of increase/decrease is inverted. As we pass upward through sugar beet and potato toward the sugar cane group, the yield of dry substance is powerfully increased with every decrease of nitrogen percentage. The ratio of nitrogenous to nonnitrogenous substance becomes smaller and smaller; the curve becomes steeper and steeper, and is obviously approaching a vertical asymptote. At the point where the ascending curve merges with this vertical asymptote a crop would contain the smallest percentage of nitrogen that will ever be found in any kind of plant, and its yield would be greater than that of any crop lower on the curve. Here the power of photosynthesis—the power that enables plants to transform solar energy into food energy—reaches its absolute maximum per unit aréa of land per growth cycle.

The curve of Fig. 3 strongly suggests the possibility of the existence of green vegetables that at one extreme would consist almost entirely of nitrogenous substance (protein) and at the other extreme almost entirely of nonnitrogenous matter (nonprotein). This broad spectrum of varied nitrogen percentage in the plants is reproduced in the same order with every change in the ensemble of the outer factors of plant growth.

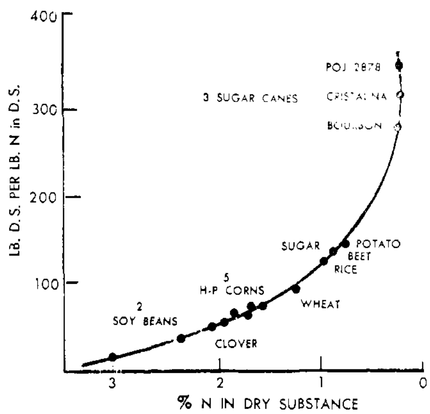


Fig. 3. The "two-way ladder of quantity of plant life." Note that upper and lower extensions of the cuive do not merge with the frame of the diagram. This is because in the lower region the plants must contain a minimum percentage of nonprotein and in the upper region a minimum of protein

Ladder of Plant Life

The curve of Fig. 3 might be described as a "two-way ladder of quantity of plant life," by which breeders of new crop plants may pass up or down, depending on their commercial interests. Wheat breeders, for instance, may wish to find strains of wheat with a high content of protein in the grain; such wheat commands a higher price. It is not difficult to breed more protein and less carbohydrate into wheat, but the trouble is that every increase in nitrogen (protein) percentage is commercially punished under the inverse yield-nitrogen law by a decrease in total dry substance, and hence fewer bushels per acre. On the other hand, the breeders of sugar crops (beet, sugar cane) have small regard for protein; what they wish is the highest possible yield of sugar and the least possible yield of nitrogen compounds.

Limits on Protein and Total Dry Substance Produced Directly from the Soil

How can these important laws governing plant life be used to determine the maximum density of population that can be sustained in reasonable comfort on the produce of one acre of arable land? Or, how can they be used to predict how long the earth's arable land can continue to feed its ever-rising population?

In its function as a two-way ladder of quantity of plant life the curve of Fig. 3 provides a key to this problem. It will now be assumed that when the density of a free-breeding population is approaching saturation, strict rationing will be established to allow an average person a daily intake of 2500 food calories, including at least 50 grams of protein. In such a ration the ratio of protein calories to nonprotein calories (carbohydrates, fats) will be 1:11.1. It then remains to select that kind or those kinds of crops which will provide the maximum yield of protein and nonprotein in just those proportions.

Reference to the ladder of plant life shows that among the major food crops the one that makes the nearest approach to this requirement is rice, wherein the average protein to nonprotein ratio in the whole dry substance (grain plus straw) is 1:11.4. However, the ladder of plant life indicates only the proportions of these components.

The next requirement is specific information on the status of the rice plant under the condominion of the law of diminishing increments and the inverse yield-nitrogen law. The law of diminishing increments limits the effective quantity of nitrogen that must be in the soil to 2230 lb./acre (regardless of the nature of the plant), and the question comes up as to how much of this soil nitrogen is metabolized into protein by rice or any other kind of plant on one acre of perfertile soil. This question is readily handled with the Mitscherlich-Baule equation, master solvent for all problems concerning the quantitative relations between quantities of fertilizer and quantities of crop yield.

Suppose that in an otherwise perfertile soil there is only one baule of nitrogen (N). The crop will absorb as much of this N as it can; the plants are unable to accept all of it. Evidently, at this stage, the mass of N taken into the crop has reached a state of equilibrium with the residual mass of N in the soil. Agrobiologically, this impasse is described as a "point of static nutrition pressure," where the pressure of the mass of N that remains in the soil is just insufficient to drive more N into the plants and cause them to produce more yield. If the N in the soil is increased to 2 baules the nutrition pressure on the crop will be increased, the plants are forced to absorb more N (but not twice as much as from the first baule) and the increase of yield will be correspondingly less. And so on. As the nutrition pressure of the N in the soil is increased by stages—up to 10 baules, say—both yield of crop and quantity of N absorbed by the plants will increase at diminishing rates while the proportion of unused N left in the soil increases geometrically until finally the crop no longer responds. (In contemporary agronomic literature frequent mention is made of the "feeding habits of plants," meaning their supposed abilities to forage for their food in the soil. The agrobiologic fact is that no plant ever "feeds itself." It takes up its food under the massed pressures of its nutrients in the soil. In a manner of speaking, it is "force-fed" by an aggressive mixture of soil chemicals that, in the agrobiologic limit, must be the same for all crops.)

The Agrobiologic Nitrogen Constant 318

Under these circumstances the original 10 baules of soil nitrogen is obviously separated into two parts: that part which has been driven into the crop and which may be designated as X_p, and that part which has remained behind in the soil to sustain the necessary mass nutrition pressure and is designated as X_s. The part of chief interest is X_p, the quantity of N that has been driven into the plants. The agrobiologic limit on the amount of this N is calculated by the formula $X_p = 2 - \log(100 - y)/0.122$, wherein 0.122 is Mitscherlich's constant for N. When this formula is duly processed, and metric units converted to U. S. units, X_p turns out with the value 318. This figure 318 is the total number of pounds of N that perultimate crops can usefully absorb from one acre of soil in one cycle. Multiplying the 318 pounds of N by 6.25 gives 1988 (in round numbers 2000) lb. as the acre-limit on protein; dividing 318 by the percentage of nitrogen in the plant gives the limit on total dry substance.

To recapitulate, all kinds of plants grown on perfertile soils are subjected to the same nutrition pressure of 2230 lb./acre of soil N. From this amount of N each kind of plant ultimately absorbs 318 lb. and converts it into 2000 lbs. of protein, which is the calculated maximum quantity of this vital food material that can ever be wrung directly from the soil in one growth cycle.

However, this yield of 2000 lb. of protein per acre is involved in a complication arising from the fact that different kinds of crops have growth cycles of different lengths. Those that have long cycles tend to absorb more N per cycle than those with short cycles. But in the long run the short-cycle ones have an advantage in that they can be repeated more often. In frost-free environments (natural or artificial) in which a series of short-cycle crops can be grown in close succession over a period of time, these crops may catch up with the longer-lived crops so that on the whole the average annual production of protein may equal or even exceed 2000 lb./acre. Therefore, in any event, the average figure of 2000 pounds of protein, corrected for the time factor, is acceptable as a minimum base for calculations relating to the food-and-population problem.

It can now be seen that the quantitative aspects of the world of plants, insofar as they relate to equilibrium between quantity of plant growth and quantity of growth factors, are measurable in three parameters. The first of these parameters springs from the law of diminishing increments, which fixes absolute limits on the effective quantities of the outer factors of plant growth; the second parameter is taken from the inverse yield-nitrogen law which genetically controls the proportions of protein and nonprotein in the plant's internal structure; the third parameter is a time factor which controls—also genetically—the tempo of the plant's metabolic processes, and, specifically, its capacity as a producer of total photosynthate per unit of time and per unit of land surface.

Equating Protein Production and Population

The next business in hand is to justify the selection of rice as a reference crop in designing a system by which a saturated population may subsist at a minimum level of comfort. Rice in its different varieties contains an average of 0.92% of N in its whole dry substance (grain plus straw); its growth cycle is about six to eight months. The possible total yield of dry substance is given by the formula 318/n, in which n is the percentage of N in the dry substance and 318 is the average number of pounds of nitrogen that any kind of plant may usefully take from one acre of perfertile soil. This formula credits rice with ability to produce a total of 34,565 lb./acre of dry substance in one growth cycle. According to previous calculations this amount will contain 2000 lb. of protein.

However, only 13,283 lb. of the total dry substance of rice is clean grain, containing 9% or 1195 lbs. of directly edible protein. The rest is diffused throughout the straw in forms inaccessible to the human stomach; a small fraction of this waste protein might be recovered, at a large loss, by feeding the straw to meat animals, but for this study it may be neglected.

The groundwork has now been laid for calculating the maximum number of persons who could be provided with a daily ration of 50 grams of protein in a total of 2500 food calories. The 13,283 lb. of clean grain of rice grown on one acre of perfertilized soil (protected from pests, diseases, drouth, and other crop hazards) has a total nutrition value of 21,080,121 Kg. calories. If one person is allowed 2500 calories a day his food intake per year will be 912,125 Kg. calories. Simple division then gives 23.11 as the number of persons subsisting on the produce of one acre of perfertilized rice. This is equivalent to a population density of 14,790 persons per square mile of arable land.

The question may be asked why rice is more valuable for feeding saturated populations than other crops, for instance wheat, which is richer in protein. Wheat stands lower on the ladder of plant life with a perultimate acre-yield of 26,948 lb. of total dry substance, including 10,388 lb. of clean grain containing 1252 lb. of protein. This much wheat with that much protein will provide 16,856,892 Kg. calories capable of sustaining 18.42 persons per acre, or 11,788 per square mile. Thus, despite its superior percentage of protein, wheat will sustain 3007 (25%) fewer persons per square mile.

Little or nothing is to be gained, directly, from crops higher up on the ladder than rice. Their gross protein content will be substantially the same, but greater proportions of it will be made inaccessible by larger proportions of nonprotein; they generally give a large excess of available carbohydrates and other energy foods which do not compensate the reduction in proportion of available protein.

No provision is herein made for anything but the two basic food elements, protein and carbohydrates (including fat). Diversion of land for fiber crops, food for animals, vegetables, or luxury crops will correspondingly reduce the calculated population density. However, future agriculturists in the service of enlightened but crowded populations may be expected to utilize all resources opened to them through knowledge and application of quantitative agrobiology. They will hardly overlook the fact that many crops do not require a whole calendar year for their growth cycles. Rice, for instance, matures in about six to eight months; under proper circumstances it could produce three crops in two years and average 3000 instead of 2000 lbs. of protein per year. This would automatically raise the critical density of population to 34.66 per acre or 22,185 per square mile; or, alternatively, it would release enough land for growing all necessary subsidiary crops for a population of 14,790.

Protein Produced Indirectly from the Soil

Time marches on, births increase geometrically, and the accumulating excess of births over deaths shows no convincing sign of reversing. Sooner or later, agriculturists of the future, forever confronted by the law of diminishing increments and the agrobiologic nitrogen constant 318, must eventually fail to keep production of protein directly from the soil in step with the birth rate. Recourse must then be had to indirect methods for obtaining supplementary protein by calling in the zymology technicians.

Take another look at the ladder of quantity of plant life. After passing upward through rice, sugar beet, and potato toward the sugar cane group the curve becomes tremendously steep, because of the rapid (geometrical) decrease of the value of n in the formula 318/n. This formula ascribes to Bourbon cane (with 0.356% of nitrogen) a perultimate yield of 89,325 lb./acre of dry vegetable matter in a growth cycle of two years, or 44,662 lb. in one year. This dry matter, consisting of sugars and substances convertible into sugars, is 80% fermentable and can yield (in round figures) 20,000 lb. of dry yeast containing 10,000 lb. of digestible protein. This is 8.4 times as much protein as can be had from one annual perultimate crop of rice grain on one square mile of land.

If this extra protein, derived indirectly from the soil, were combined with edible nonprotein food materials such as cassava and/or high-starchy potatoes grown on another acre of perfertilized soil, the two acres together would provide the basic minimum ration for 62,118 persons per square mile. If this handsome figure is discounted 50% for land taken out for subsidiary crops and for crop hazards and waste (which expert agrobiologic control should keep at a minimum), a comfortable ration might be established for 31,000 persons per square mile of arable land.

But this is not all. Above Bourbon on the ladder of plant life stands Cristalina, a sugar cane which has 12.3% more photosynthetic power. And farther up is POJ 2878, which has 11.2% more than Cristalina and which, with 0.285% of nitrogen in its dry substance, is credited with ability to give a perultimate yield of 111,579 lb./acre of dry substance. Applying the same calculations and discounts as before, POJ 2878 in conjunction with rice could serve as the basis for comfortably sustaining 36,172 persons per square mile of arable land.

But POJ 2878 is not necessarily the last word. Plant breeders may yet turn up crops with less than 0.285% of nitrogen, so the least percentage of N a plant may contain and still be a superproducer of food energy is unknown.

Until that matter is determined, the point of absolute balance between population and food produced directly or indirectly from the soil will remain undefined. Therefore, until further notice, the practicable limit on population dependent on an agrobiologically guided agriculture may be put at about 36,000 per square mile of crop land. What this means may be visualized by considering that the city of Greater New York, with a population of nearly 9 million, could be fed from about 250 square miles of nearby perfertilized soil—a smaller area than is embraced within the city's corporate limits (303 sq. mi.).

Nonagricultural Sources of Protein

The foregoing estimates on the limits of population density are based on the joint mathematical implications of the law of diminishing increments of yield in agriculture and the inverse yield-nitrogen law, which together determine the quantities of protein producible directly or indirectly from the soil. Two cases have been considered, in one of which the population depends directly on annual crops (such as rice) that yield the maximum quantity of a balanced basic ration. For this case the limit density is calculated as 14,790 persons per square mile, which could be raised to 22,185 by making the fullest use of time as a growth factor. In the other case supplementary protein is obtained by zymologic transformation of excess carbohydrate to various kinds of yeasts. This could result in a population density of up to 36,172.

Another source of supplementary protein has been opened up by the recent discovery that microscopic, chlorophyll-bearing, unicellular algae (*Chlorella*) can be grown on a large scale in fresh water containing carbon dioxide and the same chemical substances required for nourishing ordinary plants that grow in the fields. The dry substance of *C. vulgaris* consists of about 50% of protein, 32% of carbohydrate, and 18% of fats. From experimental data published by the Carnegie Institute the author has calculated that a shallow tank of water with one acre of surface exposed to sunlight would give an annual yield of about 4000 lb. of high-protein chlorella meal. When supplemented with easily obtainable nonprotein this meal could, in the limit, supply the basic ration corresponding to 24,000 persons per square mile. The necessary tanks could be located on land unfit for cultivation. The upshot would be that the produce from one acre of normal perfertilized soil could be pieced out with the produce from one square mile of a *Chlorella* farm, situated on otherwise useless land, to an extent that would sustain a population density of 60,000 per square mile.

It may be admitted that only extreme need could drive populations to take much of their protein in the form of such unflavorful materials as yeast and chlorella meal. But that would be a consequence of allowing population increase to outrun supply of animal protein. Long before the evil days actually arrive, huge populations could be supplied with beef, mutton, and milk, and much acreage that would otherwise be needed for subsidiary crops could be saved by feeding these materials to ruminants (cows, sheep, goats), whose tastes are simple and whose digestive capabilities extend much beyond those of the human stomach.

The population densities herein calculated are those attainable by employing every resource of quantitative agrobiology up to the full limits permitted under the law of diminishing increments and the inverse yield-nitrogen law.

Comfort or Malthusian Misery?

In summarizing what quantitative agrobiology has contributed to the science of plant growth and yield, it is appropos to ask: what is a science—that is, a *real* science? In answer, we may recall the words of the great physicist Kelvin, who used to say that science is measurement; that unless you can measure the thing you are studying and can express your results in concrete numbers related to some primary point or points of reference, you really know nothing for certain about it. Quantitative agrobiology has provided the plant sciences with primary rules and points of reference in a domain where none had been known before.

The culture of plants first began to acquire the status of a real science when Mendel's discovery of the law of heredity laid the foundation of the science of genetics, allowing man to create and perpetuate new kinds of plants with desirable fixed qualitative and quantitative characteristics. The second step came with Mitscherlich's discovery of the law of yield, by which the dynamic equilibria between the outer and inner factors of plant growth can be accurately evaluated.

The third and completing step was taken in the discovery of the general inverse yield-nitrogen law, by which a system of control can be established over the relative proportions of protein and nonprotein in the plant's internal structure, and which, in particular, presents a means of raising the photosynthetic powers of selected crops to near-fabulous heights.

The condominion of this triad of basic natural laws extends to every nook and cranny of the world of green plants. On this triad has been erected the framework of an over-all mathematical science of plant growth and yield which, when completed in certain collateral details (particularly the exact influence of time as a growth factor, for which more data are desirable), will enable man to take the fullest control of the earth's enormous ability to produce agricultural food, and therewith defy Malthus for perhaps many centuries.

Of particular significance in this food-and-population problem are the interlocking agrobiologic concepts of "perultimate yield" and "perfertile soil" which jointly give the measure of the maximum possible quantity of food obtainable from an acre of land and the measure of the exact quantity and composition of the constellation of growth factors necessary for producing that amount of food. Agriculturists who have qualified as quantitative agrobiologists by assimilating these two major concepts in their enveloping context, and are assigned to produce food for dense populations from limited areas of land, will have only to make the soils perfertile, and the corresponding perultimate yields will materialize—up to the limit of solar warmth and light imposed by geographical circumstances. And, given sufficient atomic or other power for generating artificial heat and light in enclosed spaces, even this handicap may be overcome when necessity demands it.

Crop Protection Important

With the nutrition of crop plants thus reduced to a matter of applying specific quantities of known materials to the soil, the practical agriculturists have only to concern themselves with defense of the plants against extraneous influences hostile to plant populations. These will include weeds, plant diseases, insects and other pests, improper soil conditions, and drouth. In proportion as these defenses are neglected or ineffective, the expectable perultimate yields will be discounted.

In the long run, of course, an unlimited increase of world population must finally overtake any means of food production now conceivable. The present generation may find complacence in the assurance that quantitative agrobiologic science, competently and intensively applied, will stave off this condition for at least a period which should give people ample opportunity to make up their minds about planned parenthood.

But it is even now a fact that large sections of the world's inhabitants have crossed the border between comfort and Malthusian misery. This is the situation that led to the creation of FAO, to whom the backward peoples have been invited by the United Nations to turn for aid in applying the remedy. And viewed only as a problem in science the remedy is now seen to be as simple as it is sure. The remaining obstacles in the way of enabling overcrowded populations to raise their agricultures to the level of their needs lie not in field technology, but in practical mass psychology and leadership in social-economic organization that will be competent to put the new knowledge into effect.

A temporary difficulty lies in the scarcity of agriculturists qualified in quantitative agrobiology. Readers of this article may have noticed several passages that impute to the general body of plant scientists—plant geneticists, plant physiologists, soil scientists, and agronomists—a deplorable neglect of the basic principles of quantitative plant life embodied in the law of diminishing increments of yield, and in the inverse yield-nitrogen law.

The author has assumed responsibility for this imputation deliberately, and advisedly. Advisedly, because the generality of plant scientists are themselves furnishing continuing evidence of lack of familiarity with, or of effective interest in, the primary points of reference that make the study of quantity of plant life a real science. The author believes that every reader who has come with him thus far will agree with the proposition that no titular professor of soil and crop science has a firm grip on his subject matter unless he has dug to the bottom of the law of diminishing increments of yield in agriculture, and hence is in a position to lead his students to see how the rule of halved increments and the mass action law apply to every quantitative aspect of the interaction between the outer and the inner factors of plant growth.

One would expect that textbooks on soils and fertilizers used in agricultural colleges would reflect this mighty principle from beginning to end. These texts do indeed contain much essential and useful information about soils and fertilizers, but with rare exceptions (and these vague and half-hearted), they convey little idea of nature's marvelous adjustments between quantitative input of growth factors and quantitative outturn of yield. Most of them do not even mention the law of diminishing increments, and then only in terms of "diminishing returns" on the input of cash and labor.

The writers of texts on plant physiology are in no better posture than the agronomists and the soilmen. This division of plant science is concerned with the inner mechanics of plant life —the absorption of plant nutrients and the metabolisms that convert these materials into vegetable substance through the process of photosynthesis. Here again is absence of awareness that there is such a thing as a measurable perultimate quantity of plant life—that nature, in her own mysterious way, has assigned to every seedling a fixed and distinct quota of vital energy which is evocable in a fixed time by a fixed constellation of outer factors that is qualitatively and quantitatively the same for every other kind of plant. Thus they miss the one essential circumstance that would give their studies complete objectivity.

Task of Plant Breeders

One of the special tasks of plant geneticists and breeders of crop plants is to bring about modification of the germ plasm of these organisms that would result in larger acre-yields of food materials. They have achieved remarkable success in producing new crops that are better yielders because of resistance to cold, drouth, pests, diseases, and other crop hazards. But in none of their texts or published research has this author been able to find knowledgeable reference to the law of diminishing increments and the inverse yield-nitrogen law as dominant determinants of quantity of plant life in the agrobiologic sense. They generally do very well with the theory of genes in the differentiation of incidental or accessory varietal characteristics, but this theory has not led them to the "marker" that unequivocally characterizes quantity of plant life. That is to say, they have yet to show awareness that nitrogen percentage in crop plants is gene enough for spotting the potential high yielders.

The conclusion is that salvation of overcrowded populations from the creeping Malthusianism that has already involved large sectors of the earth will make small headway until the plant scientists square their outlook and teachings and practice with the realities of the quantitative as well as the qualitative aspects of plant life. They should cease to ignore the very fundamentals of their disciplines and begin to turn out qualified quantitative agrobiologists by the thousand.