WHEAT STUDIES

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ENVIRONMENT, HEREDITY, AND WHEAT QUALITY

CLIMATE is more important in determining wheat quality than soil or wheat variety. The texture of soil is more important than its chemical composition, because upon it depends the soil's capacity to hold moisture. Variety in itself does not determine wheat quality, for high-protein seed, under adverse conditions, may yield grain of low protein content.

The ratio of protein to starch in the wheat kernel is largely determined by moisture conditions, especially at the time of blossoming and in the post-floral period. The wheat highest in protein content tends to be produced where summers are hot and dry, and moisture has not been too far above the minimum during the earlier stages of growth and rather scant but not too scant in the post-floral period. Longer and cooler summers, with greater abundance of moisture, tend to prolong the post-floral period; and prolongation of the post-floral period tends to reduce protein content.

Although wheat variety in itself does not determine wheat quality, some varieties within a given climate have higher protein content than others. Hence wheat quality in humid climates is susceptible of vast improvement. Stimulus toward such improvement has been lacking because improvement in quality is usually accompanied by some reduction in yield. But a new stimulus has recently appeared in governmental policies directed toward self-sufficiency of importing countries with regard to bread grains. Reduction of imports of high-protein wheat can be facilitated through development of higher-quality domestic wheats. If present isolationist policies continue, strenuous efforts to breed varieties higher in protein than those now grown are to be expected, and are likely to meet with an appreciable measure of success.

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The quality of wheat crops varies from region to region as the result of climatic conditions (apparently first emphasized by von Bibra, 1861) and the selection of different varieties of the plant for cultivation. The growers of a locality may, however, have but limited knowledge of the available wheats. Climate also dictates in large measure the selection of the variety to be grown, although the demands of the market also play a rôle in this choice. In general, it is fair to say that the average quality of the wheat of a given locality over a period of years is in the main the consequence of climatic as contrasted with weather conditions, provided the same varieties and types continue to be grown. Deviations from year to year above or below this average result from the weather and other growing conditions during the season and especially in the harvest period. Drought, excessive rain, rust which varies in severity with the weather, are among the factors that determine fluctuation in quality from year to year. The grain trade, being familiar with the average characteristics of the crop of each producing section, needs to watch these yearly fluctuations due to the vagaries of the weather, more than students of trends in world agriculture or in the world trade in wheat. For such trends, the permanent conditions that in each region determine the general character of its wheat crop are of great importance, since these permanent conditions direct in large measure the expansion or contraction of wheat farming in the different regions of the world. It is to these more permanent determinants of the general characteristics of crops from region to region, rather than to the fluctuations in quality from season to season due to the caprice of the weather, that this study is mainly devoted. However, since climate and weather are not from their very nature separable, some attention is also given to weather factors as determinants of quality.

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Quality, unfortunately, is difficult to define, for wheat is a raw material and flour a semi-manufactured article, i.e., they are producers' rather than consumers' goods. It is characteristic of many producers' goods to be valued for their performance. As the proof of the pudding is in the eating, so the proof of the wheat is in the milling, the proof of the flour in the baking, and the proof of the bread in the eating. The miller is concerned with how the wheat mills, the baker with how the flour bakes, the common man with how the bread looks and tastes. Anything approaching ideal grading or standardization is therefore very difficult, since such grades and standards should be based on performance or service tests.

The miller, other things being equal, prefers the wheat from which he can extract the greatest proportion of flour; but the baker, also other things being equal, prefers the flour from which he can produce the greatest number of loaves per barrel. He compels the miller to consider not merely flour yield in evaluating wheat but also capacity to absorb water upon which the yield of bread largely depends. The bread eater in turn insists (especially in the United States) that bread shall be white and possess a certain texture, thereby limiting the baker's choice of flour. These limitations influence the baker's demand on the miller and further modify the miller's criteria for the evaluation of wheat. High quality in wheat means, then, capacity to yield much flour capable of absorbing much water and baking out loaves that attract the bread eater. In northwestern Europe and North America, this means that the flour must have the "ability to take up and retain water and to produce a large loaf of very fine texture and with a dome-shaped upper crust" (Saunders, Nichols, and Cowan, 1922). A flour capable of producing such a loaf is said to be strong or to have good baking strength.

But the taste in bread in different countries is not the same. For example in China, except in the Treaty Ports, bread is not usually made into loaves and baked, but the dough is divided into small lumps and steamed. Some countries prefer pan bread, others hearth bread. The same flour is not necessarily the best for all types of bread. Sour-dough bread is different from the puffed-up American loaf. Moreover, other wheaten products than bread demand other qualities in flour than baking strength as above defined. For pastry, decidedly weak and starchy flour is preferable to strong flour. Very strong flours make good pastry only when excessively large amounts of fat, i.e., of shortening, are used. Weak flours require less fat (Saunders, Nichols, and Cowan, 1922). Since fat is more expensive than flour, the use of strong flour in pastry, cake, cracker, and biscuit baking means high production costs and a very rich product which is not always desired by consumers.

Finally, in some countries, the consumption of flour in unleavened products like alimentary pastes is large. The Italian types of these pastes, known as macaroni, spaghetti, etc., demand special types of wheat and in particular durum wheat, whereas noodles, so largely consumed in China and Japan, may be made from weaker flours.

It is obvious, then, that one cannot properly speak of wheat quality without specifying the purpose for which the wheat is to be used. In this study, quality with reference to the making of bread of the type of northwestern Europe and North America is the only aspect of wheat quality treated.

Before leaving this very difficult problem of defining wheat quality, it seems worth while to bring to the reader's attention that the concept of quality may change with the taste and habits of consumers or with changes in the art and practice of milling and baking. The nineteenth century witnessed one such change in the introduction of roller milling. Before that time, soft wheats were preferred to hard wheats largely because when milled between stones the former produce whiter flour than the latter (von Bibra, 1861). Hard wheats were discounted. In England, before 1877, home-grown wheat, which is weak and soft, nearly always sold at a premium over imported wheat, much of which was hard and strong. Since 1878, imported wheat has regularly sold at a premium over home grown. It is about this time that rollers displaced stones in milling. When a revolution in technology like roller milling may again occur, no one can say.

The Principal Determinants of Wheat Quality in Commerce

Wheat quality, as it is understood commercially, is the resultant of a large number of factors. These may be grouped in the following categories: (1) the presence of foreign materials; (2) the presence of damaged kernels; (3) the presence of abnormal kernels; (4) traits inherent in the wheat itself.

Foreign materials may be of many sorts: dirt of various kinds; smut balls; mold spores; weed seeds; other grains including other varieties of wheat, for example durum in hard spring. Indian and Russian wheats are often very heavily charged with foreign material. Usually such material gets into the wheat because it is garnered with it, but instances are known in which it is deliberately added for profit. How the various sorts of foreign material, including other varieties of wheat, get into the commercial grades of wheat, how they are removed, what economic consequences follow: these are questions not dealt with in this study. Here it is sufficient to point out that, to the extent to which these impurities are present, the volume and weight of wheat in the measured bushel are lowered, and expense for cleaning is involved. Sometimes the foreign material that has to be removed is valuable, as for example maize or flaxseed, and in part may reimburse the miller. When, however, the foreign matter can be removed only with difficulty or at best incompletely, as for example garlic found in wheat grown along the Atlantic seaboard of the United States, the commercial value of the wheat is seriously lowered, for the impurity must be ground along with the wheat to the detriment of the quality of the flour.[1] When different varieties of wheat are mixed, whether deliberately or as the natural result of the flow of many small parcels to market, the mixture is less highly regarded by millers than unmixed wheat (Taylor, 1926). The premiums paid in England for Canadian wheat shipped from Vancouver and the high regard attached to wheat moving by the Hudson Bay route and from Bahia Blanca are attributable in part to the fact that these wheats are more nearly uniform and unmixed.

Damaged kernels are mostly either bin-burned or sprouted. Bin-burning is due to heating during storage, and frosted and shriveled grain is especially liable to heat, in part because it respires more vigorously than normal kernels. Respiration, as explained below, generates heat, which, if the wheat is stored in bulk, cannot easily dissipate itself because grain is not a good heat conductor. Warmth creates favorable growing conditions for the micro-organisms which are always found on the surface of grain, and their activity adds to the heat which, because of the great bulk of the mass, is lost only very slowly. The ultimate result may be a rise in temperature sufficient to bin-burn the grain. According to Bailey (1925), discoloration begins when the grain exceeds fever heat (i.e., about 100° F. or 37.8° C.). The first effects noticeable are impairment of flavor and odor of the baked products. Since both respiration of wheat and activity of micro-organisms are favored by the presence of moisture, the cause of bin-burning is the storage of grain with a moisture content high enough, under the conditions of storage prevailing, to favor respiration and the activity of micro-organisms. If the temperature of the grain put in storage is low and the weather cool, a higher moisture content is permissible than when the contrary conditions obtain.

Moisture content is therefore a most important factor to be considered in evaluating quality. Not merely does it favor spoilage but it tends to lower weight per bushel and is therefore a factor of influence in determining flour yields (Neumann, 1914). Wheat with a high moisture content is sometimes termed "tough"; if the moisture content is excessive, it is known as damp wheat. In this connection, it must be remembered that grain is very hygroscopic and will absorb moisture from the atmosphere or give it up according to circumstances. Thus dry, very cold wheat transported to a warm seaport for transshipment may in the process pick up a good deal of moisture, which condenses on the grain like dew on a glass of ice water in summer. This is one of the reasons why shipment from ports in warm regions is often hazardous. Grain may pick up enough moisture to heat en route.

Sprouting sometimes takes place in the shock or stook, if the grain was not dry enough when cut or if there is warm and wet weather. Or it may occur if the grain is stored in too moist a condition, provided heating does not occur, which of course soon kills the seed. Opinions differ concerning the baking quality of flour made from sprouted wheat, but the preponderance of evidence indicates that, if the degree of sprouting is slight or if the proportion of sprouted kernels is small, the flour may nevertheless be good. Sprouting may lower flour yields somewhat. Indeed, a small proportion of sprouted kernels is said to improve flour, because of the development by the germinating embryo of the enzyme, diastase, which has power to convert starch into sugar.

The most important cause of damage then is weather as contrasted with climate, for rain at or after harvest is one of the principal causes of high moisture content of the grain which predisposes it to spoilage. If the grain is cut before it is quite ripe because frost is feared, the moisture content is usually high and the weather leaves no chance for drying out. The grain may not merely sprout; it may also become musty. In some regions, rain is so probable at or after harvest that moisture content is often high and the grain needs special handling to prevent spoiling; harvesting with the combine is too dangerous,

[1] Garlic also clogs the rolls and reduces flour yields (Metzger, 1922).

for the wheat has no time to dry out in the shock.

Neither bin-burning nor sprouting will concern us further in this paper, but some effects of storage as such need consideration. It is generally conceded that wheat improves if stored under good conditions, at least for some months. Many millers believe, however, that too long a period of storage damages wheat for flour-making purposes and they discount old wheat. Experimental evidence does not support this belief—at least for any reasonable period of storage. Saunders (1910, 1911) found wheat improved with a year's storage, and Stockham (1920) observed no reduction in quality for five years. Some decrease in strength became apparent after the sixth year. At the end of eight years, flour was milled and the bread baked at once was fairly good. This flour after four months of storage was no longer satisfactory. Saunders, Nichols, and Cowan (1922) stored wheat for five years. Some varieties improved throughout the period, while others reached a maximum in two, three, or four years, and then deteriorated a little. Mangels (1924) got less consistent results. Spring wheats showed little change; some durum wheats improved while others deteriorated with respect to baking quality. Wheat apparently loses its germinating power and becomes useless for seed before it loses its bread-making value. Perhaps the basis for the objection to old wheat is that, since it has been stored so long, it has been exposed for a long time to the vicissitudes of storage, i.e., to the danger of heating, bin-burning, and to insect infestation—particularly to attack by weevils. Weevils do damage by partially eating the grain, and their excrements are said to attract moisture and hasten moldiness (Dendy, 1919). Other vermin, for example mice, may leave a bad flavor or odor. The chances are, therefore, greater that old wheat may have been damaged than new; but there is no good evidence that age itself, if not excessive, hurts wheat for milling. As Saunders, Nichols, and Cowan (1922) put it, deterioration of stored wheat or flour does not begin until after a period of several years. The storage conditions must be good, for doubtless in a damp, unventilated room deterioration might set in earlier. Most of the work of these various investigators was not done with commercially stored grain. Possibly commercial storage is sufficiently unfavorable to justify the views on old wheat held by so many millers.

Mention needs also to be made of the cracking of kernels done by harvesting machinery badly adjusted. It is claimed, probably without justification, that the combine does more of this sort of damage than older types of machines. Longitudinal cracks along the crease are alleged to be particularly objectionable. European millers claim that such wheat has poor milling properties.

Abnormal kernels are mostly so-called shrunken or light-weight ones. These also are damaged kernels in a sense, but unlike the damaged kernels discussed above the damage was done before harvesting. Rust infection is perhaps the commonest cause of light-weight, shriveled hard spring wheat in the United States. The protein content of such wheat is often high, but not necessarily so. Apparently the effect in this regard depends upon environmental conditions as well as on the intensity of the infection. Frost sufficient to arrest growth before maturity is another cause of light-weight kernels. Their appearance and composition varies with the severity of the frost and the stage of development at which the plant is killed. When the damage is severe, the kernels are more or less blistered and shrunken. Such wheats tend to have a high nitrogen content and a correspondingly lower starch content (Harcourt, 1908), but kernels that are frozen so near maturity that they are but little shrunken or blistered may have an unchanged composition. This is a matter to which we revert below. According to Saunders, Nichols, and Cowan (1922), frosted wheat tends to give poor flour. Whether this is due to the frost or to the fact that frost usually comes in cool and otherwise climatically adverse years is an open question.

Bad weather during and after harvest and frosts and drought before the grain is mature may do damage. The first, as we have seen, predisposes the wheat to sprouting and heating; the second is one of the causes of light-weight, shriveled wheat. Dry, hot winds before the grain is ripe are also an important cause of light-weight, shriveled wheat, especially in semi-arid regions where there is no superabundance of soil moisture. Indeed, when such weather comes at or soon after flowering, there may be crop failure however favorable the climate may otherwise be.

The traits inherent in the wheat itself that are most important are weight per bushel, protein content, gluten quality, hardness or softness, and the presence of yellow-berry kernels.

Weight per bushel is directly correlated with flour yield. In general, for the same variety, the greater the weight per bushel the higher the yield of flour, as Shaw and Gaumnitz (1911) demonstrated by milling samples of known kernel size. They also found a tendency within the variety for the larger kernels to be the harder, which, it will be noted, is in the same direction as flour yields. Shollenberger (1925) found that the average yield for hard spring wheat weighing 63 pounds was 73.8 per cent, and that the average yield sank with the test weight until 51-pound wheat yielded but 62.8 per cent. The corresponding figures for hard winter wheat were 73.3 per cent and 65.5 per cent. The drop in flour yield is not quite proportional to test weight, but becomes somewhat less relatively as the test weight becomes lower, i.e., a drop in test weight of a pound in heavy wheat causes a somewhat greater drop in flour yield than a similar drop at the lower end of the series. It is obvious then that weight per bushel is a most important character for millers; more attention is paid to it in Europe than in America.

Protein content and gluten quality in their bearing upon the evaluation of wheat have been discussed in earlier studies of this series (Alsberg, 1926, 1928). Here it is only necessary to remind the reader that high protein content is almost always associated with great capacity of the flour to absorb water and to give a high yield of bread. However, great capacity to absorb water is not always a guarantee that a flour will yield good bread. According to Wynott (1926), certain Indian flours absorb a phenomenal amount of water, yet do not under normal conditions make good bread. Some Persian flour gave similar results. Wynott attributes this phenomenon in part to the nature of the starch; this suggestion may be well founded, for Alsberg (1927, 1928) has pointed out that starch as well as gluten plays a rôle in determining the water absorption of flours, while Kozmin (1930) attributes a major rôle to it. However, at bottom, the reason for the great water absorption of these Indian and Persian flours may be merely that they are very dry; Wynott does not specify the water content of those he tested. In very dry climates, at least in climates that are very dry for some time before and during harvest like the wheat regions of British India (Wright and Davis, 1927), the central valley of California (Hilgard, 1883), and in some years the wheat regions of the states of Washington and Oregon, harvested wheat may be excessively dry with as little as 6 to 8 per cent of moisture. When it is milled in a humid climate or when the flour is made to absorb moisture, a good deal more water is taken up than in the milling of less dry wheats. The yield of flour is correspondingly increased.

In the United States, where flour may legally contain as much as 13.5 per cent of moisture, the gain from absorbed moisture in the milling of very dry wheat is quite considerable. In some European countries, flour may contain as much as 16 or even 18 per cent of moisture, and there the advantage of milling very dry wheat is even greater. In Europe, and especially in Great Britain, much more than in America, millers pay attention to the moisture content of grain in buying (Ashby, 1924). Moisture content needs also to be taken into consideration in evaluating wheat according to its protein content, for obviously dryness raises and moistness lowers the proportion, though not the absolute amount, of gluten.

Since the quantitative estimation of gluten or protein (Alsberg, 1926) requires the services of trained technicians, it is fortunate that high protein content is usually associated with hardness of the wheat kernel. It is almost always found in wheat that is hard, translucent, and neither soft nor chalky, traits that are recognizable without difficulty. Such wheats are sometimes described as vitreous or flinty. Their vitreous appearance depends upon the relation of the gluten to the starch. With a sufficiently high ratio of gluten to starch, the cell contents of the endosperm are cemented together solidly as the grain dries out in ripening, while in the absence of sufficient gluten, air spaces appear within the cells rendering the grain soft and also serving as refracting surfaces that make the grains opaque. A grain of hard wheat may be made to lose its vitreous appearance by soaking it in water till it begins to swell and then drying it. This causes air spaces to appear within the berry. A true soft wheat has air spaces diffusely scattered through the interior of the berry, i.e., through the endosperm.

"Yellow berry" is said to occur in hard wheats when any appreciable proportion of the kernels tends to be light in color and soft in whole or in part. If the berry is soft only in spots, it has a mottled appearance, the lighter portions being soft and chalky and the darker portions harder. Yellow berry must not be confused with true softness. The air spaces are not diffusely distributed within the endosperm as in true soft wheat, but occur in flake-like groups with quite definite margins which may be confined to a small spot only or may include the whole endosperm. Such wheat tends to produce flour of poorer quality and is discounted by millers in proportion to the percentage of yellow berry present. The gluten content tends to be lower than normal and of poor quality. In short, yellow berry is the change in greater or lesser degree of a hard wheat to a state of softness analogous to but not identical with that of a genuine soft wheat. The conditions which bring these changes about are discussed in some detail below.

We have now completed consideration, so far as necessary for present purposes, of the major traits of commercial wheats that govern the evaluation of this grain. We have not endeavored to make any distinction between types, as for example winter, spring, and durum, and we shall not hereafter do so, although type is an important factor in evaluating grain in commerce. We shall merely point out here that the several classes or types of wheat do not react in exactly the same way toward environmental factors, but to take all these matters into consideration here would involve us in an unmanageable confusion of detail.

We shall now turn to consideration of the factors that determine the inherent traits of wheat itself, our last category of traits. These factors are of two sorts, environmental, i.e., soil and climate, and hereditary, i.e., traits inherent in the variety. It is the purpose of this study to review for the reader the more important investigations that elucidate these relationships, but their significance can only be grasped if the reader possess some knowledge of the physiology and the laws of growth of the wheat plant. To present this information is our first task.

The Physiology of the Wheat Plant

Two quite different processes are involved in building up the complex substances which form plants. The first is the absorption by the roots of water and mineral matter from the soil — potassium, calcium, phosphoric acid, nitrogen, etc. The second is the formation of carbonaceous material—sugar, starch, wood, fiber, oils, etc. These consist almost solely of the elements carbon, hydrogen, and oxygen. Unlike mineral matter, the carbon is secured not from the soil but from the carbon dioxide gas of the atmosphere. The green plant is able to absorb this gas from the air and, with the aid of sunlight, to combine it with hydrogen and oxygen derived from water to build up complex substances like sugars. The process is known technically as *photosynthesis,* since complex substances are synthesized by means of light from simpler ones. How this is done is not yet wholly understood.

The points to be noted here are that (*a*) photosynthesis takes place only in light, and (*b*) it is not directly dependent upon the concurrent absorption of mineral salts from the soil. As a matter of fact, most of the mineral salts needed by the wheat plant are absorbed before it blooms. Nitrates may still be absorbed after the time of blossoming, but under field conditions their absorption has usually been completed earlier.[1] Photosynthesis, however, continues until the plant begins to die and mature. In other words, the nitrogenous material which the plant uses to manufacture gluten is usually all or nearly all present in the plant before blossoming, whereas the starch material is produced over the whole period from the time of formation of the first leaf to ripening. This relationship is important for the reader to bear in mind.

How the plant manufactures protein is not at all understood. The process is, however, dependent upon the presence of both nitrogenous and carbonaceous material, the former brought into the plant from the soil by the roots, the latter the product of photosynthesis.

Little if any photosynthesis goes on in the developing seed; its constituents are manufactured from simpler substances transported into the seed from other organs of the plant. This process of moving material from one organ of the plant to another is known technically as *translocation.* Both the starch and the gluten are formed in the developing berry from simpler materials translocated there. The berry parasitizes, as it were, upon the rest of the plant. The starch is probably formed in the berry from translocated sugar, the gluten from translocated amino acids and amides. Since the formation of gluten is influenced by the moisture content of the berry, the amino acids and amides are not built up into gluten as fast as they are moved into the wheat kernel, but only as the moisture falls to 40 per cent.

The physiological processes we have thus far dealt with are constructive; they add to the mass of the growing plant. However, it must not be forgotten that concurrently with the constructive processes run destructive ones which lead to loss of mass from the plant. For the plant, as for all other beings, there is a cost of living; a part of the material that it builds up by photosynthesis, mostly starch and sugar, is oxidized to furnish the energy required for the plant's life processes. Technically, this oxidation process is termed *respiration.* Like other oxidations, respiration is a form of combustion and yields heat. Respiration and heat production go on, though in small degree, in the resting seed if it is not very dry; and the heat thus produced plays a rôle in initiating the heating of moist wheat stored in bulk. The materials oxidized are, of course, destroyed, so that the respiring seed loses weight, non-protein material disappearing. There is a corresponding slight change in composition, the proportion of protein tending to rise a little. This is probably the reason why protein percentage may rise slightly in storage even without drying out of the wheat.

Throughout the greater part of the life cycle of the wheat plant, the constructive process, photosynthesis, predominates enormously over the destructive process, respiration. The wheat plant, therefore, grows rapidly. However, photosynthesis seems to be more easily affected by adverse influences than respiration. It is easily inhibited by drying out of the plant, whereas respiration continues fairly actively so long as the plant contains in excess of 40 per cent of moisture. After the moisture content drops below 20 per cent, the loss of weight due to respiration is very small. Translocation is also sensitive to desiccation—probably more sensitive than respiration, for translocation of material into the kernel ceases altogether before the moisture content has quite reached 40 per cent. These relationships suggest that the rate at which plants dry out as they ripen, through affecting the rate of respiration relative to the rate of translocation, may influence the relative protein and starch content of the harvested grain.

It is obvious, therefore, that anything that affects the drying out of the plant must affect the composition of the seed. Such a phenomenon occurs at flowering because opening of blossoms increases the surface of the plant suddenly with a corresponding increased loss of water by evaporation. The loss of water by plants is known to physiologists as *transpiration.* Van de Sande-Bakhuyzen (1926, 1928) has determined by experiment that at flowering time there is very great increase in trans-

[1] For a critical résumé of the chemical changes that occur during the growth of wheat, the reader is referred to Bailey (1925), chapter iii.

piration, so that the roots may not be able to maintain the plant's water reserves. He has presented evidence that at the time of flowering some drying out may occur with permanent injury, causing the plant thereafter to dry out progressively. This sudden great demand for water at the time of blossoming has, as we shall see, an important bearing upon the composition of the ripe seed.

Since in this study we are interested primarily in the factors that determine the proportion of gluten in the seed, we need to know the progressive changes that take place in the seed as it develops. Especially significant for our purposes are the relative rates at which proteins (gluten) and starch are formed in the developing seed, for these two materials are present in inverse proportions. If the percentage of gluten is great, that of starch must be correspondingly low, and vice versa. If the two are formed at the same rate from the beginning to the end, then the duration of the period from blossoming to ripening cannot influence the ratio of gluten to protein. If, on the contrary, the rates of formation of gluten and protein are different with respect to one another at different stages of the seed's formation, then, obviously, the duration of the period from blossoming to maturity, which we shall hereafter term the *post-floral period*, must affect the final composition of the seed. If the protein is deposited at a rapid rate relative to the starch early in the post-floral period and at a slower rate relatively later in this period, then a short post-floral period must favor a high protein percentage, and vice versa.

On this point, unfortunately, investigators are not agreed.[1] Some hold that the rate of accumulation of nitrogenous material is most rapid in the beginning, others that the ratio in which starch and nitrogenous matter are deposited is fairly constant throughout. Brenchley and Hall (1909) found that the nitrogen percentage in the grains falls during the earlier stages of seed development and then remains constant till a few days before maturity, when, possibly, there is a small increase. During the period of constant nitrogen percentage, the material moved by the plant and stored in the endosperm appears to be of constant composition. They found no evidence that protein is laid down earlier than starch.

Thatcher (1913*b*, 1915) obtained results which tended to confirm Brenchley and Hall. He found a tendency toward a reduction in the percentage of nitrogen in the grain during the first half of the kernel-development period, followed by an increase in the percentage of this constituent during the latter half of the period. Gain in milligrams of protein per kernel each day was less variable than the gain in carbohydrates, the latter decreasing toward the end of the ripening period. In consequence, the ratio of carbohydrates to protein moved into the kernels diminished appreciably, and the percentage of protein in the kernels accordingly increased as the grain approached ripeness. Thatcher found further that in the last fortnight before ripening the kernels may double in weight. In the last week, the dry weight of 1,000 kernels rose from 23.9 to 25.23 grams. Any condition which interferes with the process of translocation of material to the kernel during this period, such as hot, dry winds and stem-rust infections, may operate to substantially reduce the yield and the grade of the wheat crop in consequence of the shriveled, light-weight grain which will result. Wheat must head before the weather gets hot and dry if it is to form grain (Farrer, 1898).

In very few of the investigations into the chemical changes that take place in the course of the development of the berry has attention been paid to the character of the protein laid down. Little more is done in most of them than to distinguish the nitrogen present in the form of protein from that present in other forms. Very rarely have investigators distinguished between the nitrogen of the gluten and that of the non-gluten protein. With the exception of Woodman and Engledow (1924), almost no one has distinguished between the two proteins of which gluten is composed, glutenin and gliadin. These have very different physical properties. Gliadin is nearly insoluble in water and salt solution but soluble in aqueous alcohol, while glutenin is not soluble without change in any known sol-

[1] For a review of literature, see Bailey (1925).

vent. Woodman and Engledow found that about the thirty-third day after ear emergence both glutenin and gliadin were present in equal but very small amounts. Thereafter, glutenin increased up to about the fiftieth day and then remained constant or possibly decreased slightly. The gliadin also increased but at a much more rapid rate than the glutenin, reaching its maximum at about the sixty-second day, when it was present in almost double the amount of the glutenin. It is obvious, therefore, that if the observations of Woodman and Engledow are typical for wheats in general and not a special case, the length of the post-floral period must influence the ratio of gliadin to glutenin in gluten. A short post-floral period must tend to lower the proportion of gliadin in gluten and vice versa.

At one time, it was believed that the ratio of gliadin to glutenin was a good index to gluten quality. Recent investigators have claimed that this ratio varies, if at all, so slightly as to be without significance. The problem certainly needs further study, for the findings of Woodman and Engledow indicate that some variation in this ratio is conceivable. Such studies may still disclose an important factor determining gluten quality. It may easily turn out that the relative rates of formation of these gluten proteins in the seed are different in different varieties or under different environmental conditions or both.

Moreover, gluten quality depends upon the physical state of its constituent proteins. These exist in a state of extremely fine subdivision—not so fine as molecules nor yet so coarse as to be visible under the highest powers of the microscope. Matter in this condition of subdivision is said to be in the colloidal state, and such substances are said to be colloids. Colloids are sensitive to even slight changes in their environment and are apt to respond either by becoming more finely divided or, more frequently, by clumping together to form coarser particles. It may easily be, therefore, that slight changes in the gliadin-glutenin ratio or slight changes in the relative rates of deposition may have large effects on the colloid state of gluten.

Moreover, gluten formation depends upon the moisture content of the kernel. When the moisture content falls below 40 per cent, translocation of nitrogenous substances into the grain almost ceases, and gluten is formed from such substances previously stored there. Undoubtedly, the rapidity with which the berry dries out and ripens determines the rate of gluten formation, and all we know of the behavior of colloids in general indicates that the rate of formation is an important factor in determining their physical properties.

All these are questions that await solution. They need to be placed before the reader here because wheat quality, as we shall see, is so largely determined by climate, which in turn determines, at least within limits, the length of the post-floral period.

Soil in Relation to the Wheat Plant

Nothing is less true than the old adage "dead as a clod." Every cubic foot of the soil swarms with untold numbers of microscopic plants, mostly bacteria, and with untold numbers of microscopic animals, mostly nematode worms and unicellular animalcules (protozoa). These grow and reproduce, compete with one another, and devour each other. Their presence profoundly affects the character of the soil, for they change its composition by consuming some of its constituents and by excreting their waste products into it. Even some of the larger denizens of the ground, like the earthworms, profoundly affect the texture of soil. The burrows of these worms make channels into which air may penetrate and along which roots may penetrate deeply (Opitz, 1904); they are cultivators of the soil. In their castings, they bring large quantities of deeper soil to the surface (Darwin, 1881; Russell, 1909). Not even the mineral matter of the soil is unchanging. Capillarity brings salts to the surface from the decomposing rocks underneath, and the rain leaches them out. Carbon dioxide and common salt, if present in the water of the soil as they often are, decompose mineral salts and change the character of the mineral components of the soil (Russell, 1924).

In short, the soil is the site of great activity. So long as temperature, moisture content, and other physical conditions remain constant, a balance is reached which is maintained as in any other society. In a nation, men are born and die, but the character of the nation does not change, or changes very slowly, so long as conditions remain constant. So it is in the soil. An equilibrium is established between its animal, plant, and mineral components. But conditions rarely remain constant for long. In nations, new inventions come and revolutions follow: in soils, too, there may be revolutions, for forests advance or retreat, and a series of dry years is succeeded by a series of wet ones. In the course of ages, perhaps in the course even of centuries, soils change as everything changes.

Moreover, there are seasons in the soil as in the atmosphere above. The ground is cooled off in winter and moisture content fluctuates with precipitation and temperature. With each change, the existing equilibrium is disturbed and a different equilibrium tends to be established; the soil tends to acquire a new character. For example, at one time the nitrifying bacteria — those which form nitrates—may gain the upper hand with resulting enrichment of the soil in this form of plant food. Under other circumstances, the denitrifying bacteria may dominate and cause the soil to become impoverished in nitrates.

Just how the fauna affects the composition of the soil is less understood. Russell and Hutchinson (1909) have shown that partial sterilization by heating or by certain chemicals changes soil fertility, owing, at any rate in part, to the destruction of large organisms (protozoa) which compete with and destroy smaller organisms (bacteria). The bodies of the former can serve as food for the latter.

Since soil character is so dependent on environment, it is not astonishing that the nutrient content of the soil may vary with the seasons and from season to season. A longer or shorter, a cooler or warmer, a drier or wetter summer, all have their effects upon the soil. Such shifts, even when slight, may well be important in determining crop yields and the composition of the grain.

It seems to be generally agreed that the effects of fertilizer vary with the stage in the plant's growth when it is applied. Gericke (1922) has found that the application of soluble nitrogen late in the plant's growth tends to shorten the length of the growing period of head-producing stalks without much affecting the total length of growing period of the plants. He has also found (Gericke, 1933) that larger yields of grain were obtained when the plants were offered no nutrients during the latter part of the growth period than when they were offered an abundance of nutrients throughout the entire growth period. "These results, at first consideration somewhat surprising, are, however, in full accord with the observed facts of nature, namely, that for a considerable period of their growth, many plants rooted in soil thrive in a media low or nearly depleted of available nutrients, granted of course that the supply was adequate during their early growth stage. This condition exists because plants have a higher rate of absorption of nutrients than the soil has of making nutrients available" (Gericke, 1933).

In short, the character of a soil depends not merely upon the character of the rocks from which it is formed, but also upon the conditions of drainage and upon the climate. Therefore, soils of similar composition may exhibit very different fertility in different climates. For example, certain clay and sand soils of England are poor farming land because of the cool temperature and moderate but frequent rainfall, whereas very similar soils in western Canada are very fertile because of the warm, dry summers and cold, dry winters (Russell, 1924). In temperate climates, limestone soils tend to be fertile, whereas in some tropical areas they are the least fertile. In Java, limestone soils, if they cannot be irrigated, are fit only to grow teak. In hot, dry conditions, clay may be no disadvantage and may even be an advantage, but in wet conditions it becomes a serious disadvantage. The capacity of soils to hold water is therefore important relative to climate, not in itself. The high percentage of humus in some virgin wheat soils gives them a high water-holding capacity which in large measure accounts for their fertility. However, because the soil moisture is abundant, the wheat they produce may be of lower protein content than wheat grown in the same locality on the same kind of land that has been cropped for a period of years (Shutt, 1908).

It is therefore not astonishing that under similar conditions we find very similar types of soils nearly everywhere. Black soil—the *tchernozem* of Russia and the black soil of the prairies of the United States—are widely distributed where conditions are similar: in southern Russia, Hungary, the Dakotas, Nebraska, Kansas, and some other states, and in Canada. The same is true of gray or forest-steppe soils and of peat and ashy (*podzol*) soils. The gray soils are found in strips along the northern boundary of the black soils of Russia, in western Europe, and in North America on the boundary between prairie and forest. The podsoils cover the northern parts of Europe, Russia, Siberia, and all plains of northwestern Europe. In 1907, Tulaïkoff (1908) prophesied that these podsoils were to be expected in Canada, and this prophecy has been fulfilled. Indeed, today, Canadian soil scientists are using the nomenclature of Russia to describe their own soil types. Moreover, it seems that the soils of North America occur in zones very much as they do across the Eurasian continent. There, in a general way that is correlated with temperature and rainfall, one finds a succession of soil types in broad belts across the continent as one passes northward toward the Pole (Timoshenko, 1932). A similar succession occurs in North America. The conclusion is inescapable that soil character and climate are definitely interrelated.

Russell (1924) writes: "It appears then that if a fertile soil were carried from one country to another its productive power would not necessarily be carried with it. Its fertility is, to a considerable extent, dependent on the fact that it fits in with the climatic factors in producing conditions favourable to good growth of desirable crops." Experiments of this type have actually been performed; Le Clerc and Leavitt (1910), for example, interchanged California, Kansas, and Maryland soils and grew wheat upon them. Its character in each instance resembled that of the wheat of the locality to which the soil had been transferred more than that of the wheat of the locality whence the soil had been derived.

In summary, the conclusion is inescapable that climate very largely determines soil character and that to a large extent the effect of soil upon wheat quality is likely to prove in the last analysis a climatic effect acting through the agency of the soil. This does not mean, however, that large effects may not be brought about by the soil or by special treatment of the soil. Every one knows, for example, that fertilization produces marked consequences. It tends to raise yields and increase the protein of the grain but at the expense of strength. Thus it is found that by growing a soft wheat in rich soils it is possible to give it a higher nitrogen content than a hard wheat grown where it cannot obtain so abundant a supply of food materials (Humphries and Biffen, 1907).

Climate and the Wheat Plant

The range of possible wheat culture is enormous. It has been grown commercially as far north as 58° north latitude in Canada and under the Equator in Java[1] and in Ecuador. It is reported that wheat is grown in Namaqualand, South Africa, with as little as six inches of annual rainfall (Bowman, 1931), and Poulard wheat as a hay crop in Australia with only five inches (Farrer, 1898). It is grown in northern Europe with as much as fifty inches and more. It is grown at sea-level and at altitudes of seven thousand feet and over.

To state that wheat is grown at a certain latitude or altitude or with a certain rainfall gives little information concerning the environmental conditions. A given amount of rain is a very different thing in a hot and in a cold climate. In the tropics, evaporation may be so great that rainfall is much less effective than it would be in a cooler climate. Northern Canada, for example, is a land of so light precipitation that in the latitude of Utah it would be semi-arid.

[1] During the war, wheat was cultivated in Java at higher altitudes as an emergency measure and flour was milled from it. It was grown not by natives but by a few planters who hoped in this way to lease more land than they would otherwise have been permitted to control. It would seem that in consequence planting was done where rainfall was abundant; perhaps had drier locations been selected more success might have been achieved.

Moreover, the distribution of the rainfall is important. A small rainfall in a semi-arid region may produce a good crop if it comes at the time when the plant can use it, especially if it comes so as to favor germination or before and during the time of heading. Of this, Australia yields good examples. The period from seeding to the formation of the first leaf and the time of blossoming are especially critical periods in the life cycle of the plant. The first period determines the size of the first leaf, which is important for the subsequent growth of the plant; the second determines, as we have seen, when the plant begins to dry out. With regard to the period of flowering, Hooker (1907) has shown by statistical analysis that in England cool or rainy weather at the time of flowering is correlated with high yields, and Aamodt (1933; Farrer, 1898) has shown experimentally that hot, dry wind at the time of flowering reduces yield and may indeed cause crop failure.

Yield and quality are closely correlated with soil moisture. Abundant soil moisture tends to lengthen the growing period, to increase yields, and to lessen protein content. According to McVey (1923), the protein content of the same wheat varies with the location. On hills wheat is darker and higher in protein than on low land. A crop may be mixed because a part is from the hillside and a part from the level land of the same field. There is, however, some disagreement among investigators regarding the correlation of length of growing period and protein content, due, in all probability, to the fact that some investigators have failed to establish correlation between the length of the total growing period of the plant from germination to ripening and the protein content of its seed, while others have found such correlation either with the length of the post-floral period or with the age of the individual tillers or stools. Roberts (1920) has critically reviewed the more important publications. The preponderance of evidence seems to favor the view that a short post-floral period makes for high protein content which in turn is highly correlated with high quality (Zinn, 1923). Some of the difficulty in interpretation arises out of the fact that wheat tillers or stools. We do not know whether a plant that tillers is an individual or a colony, nor yet whether one tiller can profit by the activity of another, nor whether late tillers which fail to form an ear are, in relation to yield, a help or a hindrance. It is necessary, therefore, to treat the tiller as the unit rather than the whole plant, as is the common practice. The importance of this point is clear from a chance observation of Biffen (1908), who found on one large, coarsely grown plant of the soft winter wheat, Squarehead's Master, which he examined ear by ear, a range of 2.6 to 1.8 per cent of nitrogen, the ears with the highest percentage being side tillers which had failed to mature properly.

It is, therefore, not astonishing that in dry climates irrigation tends to increase yields and lower protein content as compared with wheat grown in the same locality without irrigation. The extent to which this occurs depends, of course, upon the intensity of the irrigation and upon the time when the water is applied. The reader should keep in mind that irrigation acts not merely by supplying the plant with moisture but also by leaching out salts or carrying them from the surface layers down deep into the soil where they may not be as accessible to the plant's roots. In short, irrigation upsets the existing soil equilibrium. Keeping in mind the fact that varieties react differently, it is, therefore, not significant that, while the majority of investigators have found that irrigation tends to cause the crop to be of lower protein content, a few have not had this experience.

Furthermore, moderate precipitation at frequent intervals usually results in a lower protein percentage than the same amount of precipitation in a few heavy rains (Bailey, 1913). This may be due either to the fact that the run-off from heavy rains is apt to be greater, or to the fact that the nitrates are more leached out of the upper layers of the soil by heavy than by light rains. Light rainfall and large evaporation, which concentrate the nitrates in the upper portion of the soil where they may readily be obtained by the plant, seem to favor the formation of hard, glutinous wheat (Lyon, 1910).

Where the distribution of the precipitation is unfavorable, it is sometimes possible to adapt the methods of culture to the prevailing conditions of rainfall, such as seeding early or late, as circumstances require, in order to prevent blossoming from taking place at a time when there is usually no rainfall or in order to prevent the post-floral period from coming at a time when there is usually a good deal of rain. Or a variety may be selected that blooms at the time when there is least danger of drought. This procedure has been recommended by Brounov (1910). An example of such a practice is to be found in California where spring varieties are planted in the early winter, after the coming of the rains permits plowing, and harvested in the late spring or early in the summer which is rainless. Shaw (1913) has shown that in California if the fall rains come early it is best to delay planting so as to postpone the last part of the post-floral period well into the rainless summer, whereby the protein content of the wheat is raised materially.

To state that wheat has been grown at a certain altitude or latitude is also not very informing. Obviously, the effect of altitude depends upon the latitude. It is possible to grow wheat in the tropics at six or seven thousand feet, as on the central plateau of Mexico, but impossible in Canada. It is commonly stated that cultivating crops at higher altitudes is equivalent to growing them at higher latitudes; that each 400-foot rise in altitude is equivalent to an approach of one degree nearer the Pole (Smith, 1920). Such a statement assumes that altitude changes environmental conditions in the same way as latitude, whereas in fact with change in latitude there is change in the relative lengths of day and night but not with change in altitude. Yet the ratio of daylight to dark determines the time of flowering for many plants, as Garner and Allard (1920, 1931) have shown. Some species are adjusted to a very definite ratio. Some tropical plants like tobacco continue vegetative growth without flowering in northern climates, or flower only after a long time, if the ratio of sunlight to dark hours is very different from that to which they are exposed in their natural habitat. Other species are very little affected. Wheat is only moderately sensitive in this regard. The spring variety, at least, flowers and matures seed under continuous illumination, but it matures somewhat earlier (van de Sande-Bakhuyzen, 1928) than it does in the field.

As wheat is grown nearer and nearer to the Pole, its maturity is hastened, and this is a very important factor in determining that it may be grown at high latitudes, as it is in western Canada (Allbright, 1933). Shutt has shown for Canada that Marquis wheat, although seeded later at Fort Vermilion than at any other point he studied except at Edmonton, ripened earlier there than at Lacombe, Edmonton, or Beaver Lodge—localities far to the south. Fort Vermilion is 600 miles north of Lethbridge, but some 2,100 feet lower. Wheat matured there in 1.4 less days than at Lethbridge and in only 3.4 days more than at Ottawa. The Fort Vermilion yield was highest of all, being 50 bushels and 45 pounds. This was almost 50 per cent more than at Ottawa and slightly greater than at Lacombe, where a fortnight longer was required to mature the crop. It is also significant that wheat matured at the northerly point in 1.1 days less than on the dry land at Lethbridge and 9.5 days sooner than on the irrigated land (Allbright, 1933). The correlation between the length of the maturing period and abundance of moisture is here strikingly brought out.

So far as yield is concerned, there seems to be an optimum rainfall varying perhaps with the variety and certainly with the climate. Here, however, we are not concerned with a study of what determines yields (cf. Alsberg and Griffing, 1928). As a rule, yield and quality do not go together; usually low-yielding regions tend to produce high-quality wheat and vice versa. Also the spring varieties grown in regions to which they are adapted tend to yield less and produce higher-protein wheat than the winter varieties grown in regions to which they are suited. The bulk of the world's high-protein wheat is produced where yields are on the average less than twenty-five bushels to the acre — commonly less than twenty bushels and often less than fifteen bushels. But to all this there are exceptions, as witness the yield of over fifty bushels at Fort Vermilion above cited. One thing seems reasonably certain: high-protein wheat is almost always found where the rainfall, making due allowance for soil texture and for climate, is relatively scant. Under such conditions, increasing the space between the rows tends to increase protein percentage, whereas irrigated wheat grown in the same locality is not so affected (Olson, 1923). High-protein wheat is most commonly produced where there is danger of drought and, therefore, the world's crop of such wheat fluctuates considerably more from year to year than the world's supply of soft wheat.

It must not be forgotten in evaluating the effects of climate that it acts not merely directly upon the plant but also indirectly through its action on the soil.

When we come to consider temperature, we find that hot, dry summers favor high-quality wheat production. And so we see that where summers are cool and rainfall abundant, as in England, wheat is low in protein and the flour from such wheat of poor baking strength. In such countries, it is customary to import high-protein wheat for blending with the domestic product in order to produce good bread flours. In the Great Plains region of the United States and in western Canada where the summers are hot and the rainfall scanty, the wheats tend to be high in protein and strong. This may be due in part to the fact that hot weather favors nitrification and the accumulation of an abundant supply of nitrates in the earlier growth stages. Also, hot weather by evaporation at the surface of the soil tends to draw soluble soil constituents to the surface by capillarity. Also, it increases transpiration and thus may favor absorption of nutrients from the soil.

As for sunlight, it would seem that there is no evidence that a lack of it is much of a factor in determining rate of growth in the open field. In England, crop plants apparently exhibit an efficiency in using the sun's energy of not over one per cent (Russell, 1924), and ordinary daylight has to be cut down to from one-third to one-fourth of its normal intensity before much effect upon the growth rate is observed (Brown and Escomb, 1905). Shaw (1913) grew wheat in the open field under various degrees of shading and found little effect, except upon the protein content of the grain, until sunshine had been reduced to from one-half to one-third of normal. Protein content tends to be reduced when wheat is grown in the shade (Thatcher, 1913*a*), probably because the cool conditions under shade prolong the growing period.

Wheat Variety[1] and Wheat Quality

As we have seen, climate is an important factor in determining wheat quality; indeed, it is generally regarded as more important than variety. In a general way, this is true. A wheat variety that is capable of producing hard, flinty kernels in one climate will not necessarily produce them in another. In California, for example, spring varieties like Marquis are commonly sown in the fall or early winter after the onset of the rainy season permits plowing, and harvested in the late spring or early summer. They are always soft, often affected with yellow berry, and yield a flour of little strength. Grown in Montana, North Dakota, or western Canada, this variety produces hard, flinty kernels, yielding flour of the best quality. On the other hand, a typically soft wheat tends to be harder and of higher nitrogen content in some climates than in others, though it does not ordinarily become as hard as typically hard wheats do under favorable conditions. This has been shown strikingly by the experiments of Le Clerc and Yoder (1914). They grew crops of wheat in California, Kansas, and Maryland from seed grown in the other localities. The crop obtained tended to resemble the general wheat type of the region where it was grown rather than that of the region from which the seed came (Le Clerc and Leavitt, 1910).

While it is true that, in a general way, climate is more important than variety in determining quality, it by no means follows that there is no correlation between wheat variety and quality (cf. Roberts, 1920). In the same climate, different varieties produce crops of

[1] The word "variety" is used throughout this study to designate a specific kind of wheat, such as "Marquis," "Fife," "Gold Coin," or "Federation," and not a type or class of wheat, such as "spring," "winter," or "durum."

different quality. There is, therefore, broad scope for improvement of wheats suited to any given locality. As has been shown by Biffen for England in the breeding of Yeoman wheat (Humphries and Biffen, 1907), by wheat breeders in Argentina, and by others elsewhere, it is possible to develop varieties that will give relatively high-protein wheats in regions where the wheat commonly grown is soft and weak. We are barely at the beginning of this work, for it is only in recent decades that it has been undertaken seriously on any considerable scale. Formerly, the aim of wheat breeders was primarily directed to the production of high-yielding varieties adapted to a given locality; indeed, it led to decided deterioration so far as bread-making qualities are concerned (Neumann, 1922). Breeders paid attention to yield, stiffness of straw, resistance to drought, to frost, and to disease. Little attention was paid to quality, for the wheat trade was slow to pay premiums for quality, as quality is understood today, and breeders were slow to change their objectives even after quality became an important element in the commercial evaluation of wheat.

The greatest incentive to breeding for quality has been given in recent years by the strenuous efforts of many nations to achieve self-sufficiency in regard to their food supply. An important step in this direction is clearly the improvement of the quality of domestic wheat and much has already been accomplished in this direction. The successes already achieved bode ill for wheat-exporting countries so long as the policy of self-sufficiency dominates the minds of statesmen.

Unfortunately, it is difficult to combine high yields and high quality in a wheat. In many localities where higher qualities might be grown, poorer wheats are cultivated because yields of the latter are so high that they are more profitable than the former. Thus a committee appointed by the Royal Agricultural Society of Denmark began investigations in 1882 and reported in 1896 that it was not profitable under their conditions to grow wheats of greater strength and pay for it with a smaller yield (Humphries and Biffen, 1907). Where the breeder has been willing to sacrifice something in yield, much has already been accomplished. It has already been possible to produce wheat of fair though not of highest quality and with fairly good yield in countries where wheat has heretofore been always weak. This is especially true in the more humid countries of northwestern Europe, and also in Argentina. While these wheats are not equal in quality to the best wheats from semi-arid regions, and while perhaps the highest qualities may never be grown in western Europe, nevertheless the raising of the gluten content of a country's wheat crop by as little as one per cent may greatly affect its wheat-import requirements. The higher gluten content of the domestic crop lowers the need for high-protein wheat to blend with it so as to produce tolerably satisfactory bread flour. Consequences upon future world wheat trade may well be profound.

Moreover, it is also possible that something may be done by selection within the variety. Different strains of the same variety do not seem to be absolutely identical in their behavior in all respects. This seems to be true to some extent at least with reference to hardness. Shaw (1913) planted starchy and glutenous seed of the same variety and crop and found "the quality of the seed used, to some degree at least, determines the character of the resultant crop, for it will be noted that as the originals decrease in both percentage of typical kernels and protein the progeny in each case decrease in the same order, although the effect of this is materially lessened and sometimes almost entirely overcome by the character of the season, as shown by the other results."

The Relations of Soil, Climate, and Variety as Determinants of Wheat Quality

In short, the hardness of wheat is a function of all our three variables. The interplay of variety, climate, soil, and cultural factors is well illustrated by the occurrence of yellow berry in hard varieties. It occurs in many places in the United States, especially on the margin between hard spring-wheat areas and winter-wheat areas, for example in Nebraska, and, as mentioned, in California where hard spring wheats are grown like winter wheats.

The conclusions reached in the numerous

investigations of yellow berry have not been uniform. Roberts and Freeman (1908) concluded that the existence of yellow berry can be ascribed only to the influence of the weather before harvesting the heads, or to inherent tendencies in the varieties themselves, or to both. It is apparent that shortening the fall vegetative period and the total length of the growing period tends to reduce the incidence of yellow berry, and that certain strains are more liable to produce it than others.

Headden (1915), on the contrary, as the result of experiments in fertilization with nitrogen, phosphorus, and potassium, concluded that climatic conditions do not cause or influence the development of yellow berry. He claims that it can be very much lessened or entirely prevented by the application of fertilizer supplying a sufficient quantity of available nitrogen. Yellow berry can be greatly intensified or increased by application of available potassium. The application of available phosphorus has no apparent effect upon its prevalence. Yellow berry is not indicative of an exhausted soil, that is, one which will not produce abundant yields. Yellow berry indicates that potassium is present in excess of what is necessary to form a ratio to the available nitrogen present advantageous to the formation of hard, flinty kernels. Headden concludes that yellow berry is under control of the grower. It can be prevented by any of the procedures which increase the available nitrogen of the soil to the proper degree. These are (1) judicious use of sodic nitrate, (2) thorough cultivation of the soil with the application of nitrogenous manures, (3) rotation with clover or other legume preceding wheat, and (4) fallow cultivation.

In a later paper, Roberts (1919) reached the conclusion that the common causes for production of yellow berry overshadow any differences that may have been due to hereditary tendencies. The later the date of ripening the greater is the tendency to show higher percentages of yellow berry. Yellow-berry kernels tend to be higher in moisture and starch content and lower in protein and ash than the hard, flinty kernels. The Oregon Station reports (1920–22) that plots cultivated in such a manner as to stimulate nitrifying bacteria produce a crop with the lowest percentage of yellow berry, the amount of available nitrogen thus appearing to be a factor. Jones and Mitchell (1926) have pointed out that in dry farming thorough tillage of summer fallow as contrasted with neglect or poor tillage results in larger yields of grain and straw, both substantially richer in protein and the grain correspondingly less infected with yellow berry.

Yellow berry, then, has been attributed to climate, to late maturity, to insufficient available nitrogen in the soil, and to variety, that is, to a hereditary character. It would seem without looking at the matter closely that these explanations are contradictory. In fact, however, all these factors may well work together, one predominating under one set of circumstances and another under another.

It is worth analyzing the causes of yellow berry further, for such an analysis may be the key to the understanding of the factors that determine the character of the wheat of different regions. Climate and insufficient available nitrogen in the soil may well both be among the causes of yellow berry. As we have seen, climate in considerable measure determines the character of the soil. Heavy rains may leach out the soluble nitrogen at just the time when it is most needed. Fisher (1925) has studied this phenomenon at Rothamsted and, on the basis of the statistical analysis of yields in the same field over a long period, attributes to this phenomenon a causal relation to yields. Gericke, as above pointed out, has shown that the application of fertilizer is especially effective at certain stages of the wheat plant's growth. He has been able to influence the protein content of wheat through the application of fertilizers at the proper time. In view of the interrelation between climate and soil composition, it is not surprising that some investigators have attributed yellow berry to climate while others have attributed it to lack of available nitrogen. Probably both explanations are true, for climate may well act through its effect on the composition of the soil.

Perhaps here also is to be found the explanation for the phenomenon that the hardest wheats are produced in the drier regions. It is well known that in them nitrification is favored and the soil is liable to carry considerable nitrate. Furthermore, this hypothesis would explain the beneficial effects of fallowing, for it has been shown recently that summer fallowing tends to increase the amount of nitrogen available. This hypothesis is not inconsistent with the belief of some investigators that some varieties are more subject to yellow berry than others. There is a good deal of evidence that a short post-floral period tends to be characterized by high protein content of the grain produced. Some of this evidence may be cited. Shortening of the fall vegetative period and of the total length of the growing period tends in Kansas to reduce the incidence of yellow-berry (see below) wheat with low protein content (Roberts and Freeman, 1908). Gericke has shown that applying nitrogenous fertilizer late in the plant's growth tends to shorten the post-floral period and to raise the protein percentage of the grain decidedly. Roberts (1919) found that the later the date of maturity the greater the tendency of the crop to show higher percentages of yellow berry. Shaw (1913) has found in California that irrigation which tends to lengthen the post-floral period reduces protein percentage and also that planting early, which under California conditions also tends to lengthen the post-floral period, reduces protein percentage. And, finally, for the most part, the highest-protein wheats are produced in the drier regions where conditions are not favorable for a long post-floral period.

As we have seen, the time of flowering is a critical period for the wheat plant. At that time it begins to desiccate and its ultimate death is determined. It seems entirely reasonable to assume that the degree to which it is desiccated and injured at that time has a profound effect upon the subsequent life of the plant. We know that it is a most important factor in determining yield (see above, p. 240). It is not improbable that it also is a factor in determining the ratio of protein to starch that is laid down in the seed. We know that desiccation reduces the rate of photosynthesis, and it seems reasonable to assume, therefore, that if desiccation at the time of flowering is considerable the rate of sugar and starch formation thereafter must slow up. If it does, one would expect the ratio of protein to starch laid down in the seed to be shifted in favor of the protein, with the result that the gluten percentage of the berry would be raised. Possibly, it is this behavior of the plant at the time of flowering and during the post-floral period that determines the proportion of protein in the ripe grain.

This hypothesis—and it is merely a hypothesis—would explain a number of well-known phenomena. It is consistent with the fact that not merely climate and soil, but also variety, are factors in determining the protein content of the wheat berry. It is well known that wheats differ in their resistance to drought. A drought-resistant variety adapted to a dry climate would be expected to possess a relatively short post-floral period, and, when grown where there is an abundance of moisture, to be little injured at the time of flowering and hence to produce wheat lower in proportion of protein to starch. Moreover, because of the dry conditions prevailing during the post-floral period, most varieties adapted to dry climates are of necessity rapidly maturing sorts. Perhaps, too, they possess a short post-floral period. Unfortunately, data do not seem to be available in the literature on the length of the post-floral period of all the different wheat varieties under the same growing conditions, nor have sufficient studies been made correlating the length of the post-floral period with protein content of the seed. Such information is badly needed, for it may well turn out that high protein content will be found to be correlated with a short post-floral period, and that varieties with a naturally short post-floral period tend to yield higher-protein grain, other things being equal. According to Engledow and Wadham (1924), the time of flowering and the time of ripening, i.e., the length of the post-floral period, are varietal characters.

SUMMARY[1]

Most of the plant nutrients derived from the soil are taken up before blossoming and

[1] The reader will find amplification of much in this summary in Bailey (1925), chapters iii and iv.

later translocated to the growing kernel. Nitrification in the soil is active early in the season and favored by hot weather. Nitrate formed in the soil may be leached out, depending upon the distribution and amount of rainfall. At the time the plant blossoms, it can still absorb nitrogen with resulting increase in gluten content of the grain. When and how much nitrogen is absorbed by the plant depend upon climate and the amount and distribution of rainfall. Ordinarily, nitrate is diminishing or present in less than optimal amount at blossoming time, but the weather and other conditions determine how much is available for absorption and how much is actually absorbed. The ratio of protein to starch in the wheat kernel is largely determined by moisture conditions, especially at the time of blossoming and in the post-floral period. If the atmospheric humidity is fairly high and there is sufficient soil moisture available to the plant, the post-floral period tends to be prolonged, relatively much starch tends to be deposited, and a plump, starchy kernel tends to result. If sufficient nitrogenous material has been absorbed before or during blossoming, and if moisture conditions are such as not much to prolong the post-floral period, the grain tends to be plump and fairly high in gluten. When moisture has been not too far above the minimum during the earlier stages of growth and rather scant but not too scant in the post-floral period, this period tends to be shortened; there tends to be abundant nitrate formation and corresponding nitrogen absorption by the plant before blossoming; starch deposition tends to be interfered with relatively more than gluten formation; and, finally, small-berried kernels, rich in gluten, tend to result.

Climate is more important in determining wheat quality than soil or wheat variety, though the last two are by no means negligible.

Cool summers with high rainfall and a relatively long growth period result in the grain of wheat being high in percentage of starch and low in percentage of protein. Hot, dry summers, on the other hand, result in the production of wheat having a high percentage of protein. In general, sufficient available moisture during blossoming and the post-floral period and weather not so hot nor so hot and windy as to cause the water losses from the plant (transpiration) to be greater than absorption through the roots can make good have a tendency to prolong the post-floral period, to favor the deposition of starch, and to lower the relative protein content of the grain.

The texture of soil is more important than its chemical composition, because upon it depends the soil's capacity to hold moisture. Soils capable of holding much moisture in a form available to the plant tend to produce low-protein wheats and vice versa.

Variety in itself does not determine wheat quality, for high-protein seed, when planted where the growing season is long or the rainfall abundant, tends to yield grain of low protein content. In a given climate, some varieties have a higher gluten content than others. Therefore, while it is not possible in a humid climate to produce high-quality wheat, it is possible vastly to improve the quality above present levels. Improved varieties for humid climates have already been developed in certain countries and much more could be done under sufficient stimulus. Hitherto such stimulus has been very largely lacking because improvement in quality is usually accompanied by some reduction in yield. However, a new stimulus to the development of varieties that yield grain of moderately good quality in humid climates has appeared in recent years. It is the policy of many countries to achieve self-sufficiency with respect to bread grains. If such countries were to raise the quality of domestic wheat even to a slight extent, the quantity of imported high-gluten wheat required to grade up domestic wheat in order to produce good bread flour might be greatly reduced. If present isolationist policies continue, it is to be expected that we shall see strenuous efforts in humid countries to breed varieties that will not be so poor in gluten as are now grown. An appreciable measure of success is to be anticipated, though truly high-quality wheats such as are grown in semi-arid countries are not likely to be produced in humid countries.

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