5.

Resource Substitutions in Agriculture

CHANGES in agricultural production functions and relative factor prices have had important impact on demand for all specific resource categories in agriculture. In general, capital in its aggregate form has served as a substitute for both labor and land. But, as mentioned previously, the many specific categories of capital have served as substitutes among themselves. For example, as Figure 5.1 indicates, total farm power inputs have been highly stable relative to the substitutions which have taken place between mechanical and farm produced sources. In most of the analysis which follows, we are interested in highly aggregative categories of capital, such as operating inputs and farm machinery. But changes in prices and productivities within these categories, with increase in demand for one specific capital item and decline for another, has had important impact on the organization of agriculture as measured by the size of the work force, the demand of the individual farm for land and hence the size of farms, etc. The "first round" and simple substitution of one specific capital item such as hybrid seed for another such as open-pollinated corn has had the "second round" effect of causing capital in the form of seed to be substituted for labor, and even for land. That is, fewer units of labor and land are needed to

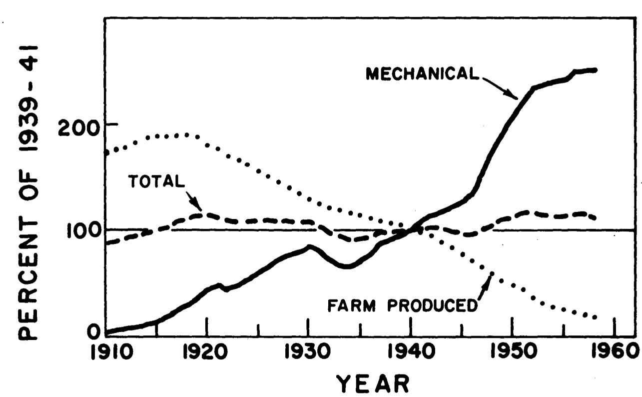

Figure 5.1. Trends in farm power from mechanical, farm-produced and total sources. (Source: USDA.)

produce rather "fixed" quantities of farm products demanded by consumers. The "first round" substitution of mechanical power for horse power has had the "second round" effect of causing machine capital to be substituted for land, as fewer crops were needed for farm production of power and could be diverted more directly to food use. Similarly, the substitution of large-capacity field machines for smaller or horse-drawn equipment also eventually allowed capital to be substituted for labor. But because of the nature of the cost economies involved, and the economic complementarity between machinery and land inputs for the firm, the individual farm demand for land grew, causing the size of farms to increase while the number declined.

BROAD STRUCTURAL CHANGE

If we were to explore fully the forces which have changed the structure of agriculture, we would need to examine all of these particular resource categories. For an over-all analysis of the organization of agriculture, particularly in respect to labor employed and the size and number of farms, this degree of refinement is not necessary. It is of concern, however, to the numerous firms which supply the inputs used by agriculture. The substitution of tractors for horses directly reduced the demand for the product of harness-making firms. The supply price of harness could not be lowered sufficiently to retard the complete mechanization of agriculture, with the result that harness firms either went bankrupt or shifted to other products with higher income demand elasticities in a growing economy. In contrast, the substitution of genetically superior seeds for farm selected ones caused the demand for the products of the commercial seed sector to grow, and probably to decline in price elasticity. Genetic improvement of both crops and livestock have lifted the restraint of the growing plant or animal on production, increasing the potential productivity and demand for insecticides, herbicides, antibiotics and other drugs and chemicals. But this growth in productivity and demand again decreases the amount of land and labor in farming to meet a given food demand quantity for the nation.

In general, an empirical approach which leads to examination of only broad aggregates of resources, or only of the aggregates which have continued to be employed in agriculture, causes us to overlook or misinterpret some of the important structural changes which relate to agriculture. The growth of the agribusiness sector of the economy, particularly firms supplying inputs, is a result of the substitution of some particular capital categories for others, and of capital in aggregate for land and labor in farming. One type of labor skill has been substituted for another as production of tractors replaced production of horses and as energy sources shifted from farm crops to petroleum and electricity. Capital inputs for producing farm resources have shifted from horse barns to tractor factories. In 1910 nearly all power used was produced on farms. But by 1960 less than 10 percent came from this source and over 90 percent came from power produced in the business sector. Demand for college-trained personnel, and the type of training most appropriate, has shifted relatively from primary agriculture to the agribusiness sector which provides a growing proportion of inputs for the farm sector. These are part of the structural changes which surround and relate to agriculture. As in the new combinations of resources used within agriculture as a result of economic development, this shift from the farm to factory production of inputs for agriculture also is largely a function of changing factor prices and technical knowledge or coefficients.

While changes in substitution coefficients directly affect the demand for products of particular firms and sectors which supply inputs to agriculture, the resources of this study do not allow interpretation of them. Instead, we examine and illustrate some substitutions among particular categories of resources. We also examine some of the broad substitutions which have taken place during the period from 1910 to the 1960's as these relate to possible resource savings in meeting the nation's demand for the output of agriculture.

FORMAL SUBSTITUTION ESTIMATES

If accurately specified and aggregated production functions were available over time for the particular crop and livestock commodities of farms operating under specific soil and climatic environments, we could better measure the effect that technological change has had on factor demand and on the product imputable to increase or decrease in specific categories of resources.

Derivation of Substitution Rates for Land

For purposes of national policy and programming, it would be useful if we had definite knowledge of the marginal rates at which capital in its various technological forms, labor in its various skilled capacities and land of various types can and do substitute for each other. Currently, aggregative data cannot be easily "decomposed" to provide these specific quantities. We are, however, able to estimate some gross marginal rates of substitution between certain factors in agriculture under specified conditions. A resource which has served as an effective substitute for both land and labor has been fertilizer. It substitutes for land since a given product can be produced with less land if fertilizer is used on the remaining acreage. It also substitutes for labor in this physical manner: fertilization of an acre boosts yield but increases labor requirement by a very small absolute amount, and as a minute fraction of (a) the total labor used per acre and (b) the relative increase in per acre yield. A given aggregate of product can be thus produced with less labor, as well as with less land.

We examine some gross substitution rates, indicating marginal replacement rates between fertilizer and land where we do not concern ourselves directly with other "minor" capital forms which also are concerned. The purpose is to provide some initial estimates of substitution rates among specific factor categories. The marginal rates of substitution between fertilizer and land are derived from experimental data. They refer to particular soil, climate and other environmental factors. As more data become available, important insight can be obtained on realized and potential substitution rates between resources such as land, fertilizer and labor. This type of information is useful in a developed economy such as the U.S., but especially so for less developed countries where food supply is low and where limited land area restrains production under current technology.

Numerous fertilizer production function studies have been conducted under experimental conditions. These studies show the response in yield per acre when various quantities and mixes of fertilizer nutrients are applied per acre; i.e. land is held constant while fertilizer is varied. Output then is specified as a function of fertilizer alone as in (5.1) where Z is yield and X is fertilizer input per acre. A more exact form of (5.1) is (5.2), where Y is total output, A is acres and F is total fertilizer.

$$Z = f(X) \tag{5.1}$$

$$Y/A = f(F/A) \tag{5.2}$$

Total output per acre (yield) Y/A is a function of total fertilizer input per acre F/A. Multiplying both sides of (5.2) by A, total output is expressed as a function of A acres and F inputs of fertilizer. We illustrate this transformation by a simple algebraic form (5.3) common in production function studies. (The same procedure may be used with other algebraic forms.)[1]

$$Z = a + bX - cX^2 \tag{5.3}$$

$$(Y/A) = a + b(F/A) - c(F/A)^2 \tag{5.4}$$

$$Y = aA + bF - cF^2A^{-1} \tag{5.5}$$

Since Z and X are per acre quantities, (5.3) appropriately is written as (5.4). The <u>per acre</u> production function with land fixed in (5.4), the type of function estimated from an experiment, is transformed to the "long-run" function in (5.5) with total output Y a function of variable land inputs A and total fertilizer inputs F by multiplying (5.4) by A. If the number of acres and the amount of fertilizer are increased by a given

[1] For a discussion of various algebraic forms of production functions, see Heady, Earl O., and Dillon, John L. Agricultural Production Functions. Iowa State University Press. Ames. 1961.

proportion in (5.5), total output increases by that same proportion. Two hundred bushels of corn can be produced with 2 acres and 100 pounds of fertilizer, or 100 bushels can be produced with 1 acre and 50 pounds of fertilizer. This assumption of constant returns to scale arises from the method of estimating production functions under experimental conditions. The function (5.3) or (5.4) applies to a given acre and, to generalize for A acres as in (5.5), the assumption is that the original conditions are replicated on each additional acre.[2] Thus (5.5) embodies the assumption that each land input contains the "fixed" experimental conditions including temperature, rainfall, soil structure, seed, machinery, etc. Similarly each fertilizer input is accompanied with appropriate labor, machinery and other inputs necessary for applying fertilizer. Under these conditions, constant returns to scale in (5.5) is a reasonable assumption.

The isoquant equation (5.6) is computed by solving (5.5) for A.

$$A = \frac{Y - bF + \sqrt{4acF^2 + (Y - bF)^2}}{2a} \tag{5.6}$$

The isoquant equation indicates the various combinations of land and fertilizer which will produce a given output Y. Taking the derivative of (5.6) with respect to F, the "gross" marginal rate of substitution of fertilizer for land can be computed. The term "gross" is used because, as indicated above, "fixed" inputs such as seed, machinery, labor, etc., are associated with land A, and "variable" inputs such as additional labor and capital required to apply fertilizer are included with F. The equation defining the marginal rate of substitution in terms of F and A (the negative ratio of partial derivatives with respect to F and A from [5.5]) is given in (5.7). If A = 1, the equation for gross marginal rates of substitution is (5.8).

$$\frac{dA}{dF} = \frac{2cFA^{-1} - b}{a + cF^2A^{-2}} \tag{5.7}$$

$$\frac{dA}{dF} = \frac{2cF - b}{a + cF^2} \tag{5.8}$$

Numerous estimated production functions include more than one variable input as in (5.9) where X and Z are different nutrients. Many proportions or mixes, including those which trace out the expansion path, can be derived from such functions.

$$Y = a + bX + cF - dX^2 - eZ^2 + fXZ \tag{5.9}$$

To reduce the tremendous detail necessary to select the optimum mix

[2] The procedure does not require that fertilizer be used in fixed proportion to land. By holding A constant in the equations, we can still vary fertilizer and obtain diminishing productivity.

of nutrients for each level of output, a mix is used equal to the proportion of nutrients historically used or recommended in the location where the data are derived. The conversion is as follows where r units of Z are specified for each one of X, or Z = rX to produce one unit of F or fertilizer. With F, X and Z all measured in pound units, a given quantity of fertilizer is composed as in (5.10). Or, the values of X and Z, in terms of F, are those in (5.11) and (5.12).

$$F = X + Z = (1 + r)X \tag{5.10}$$

$$X = \frac{F}{r + 1} \tag{5.11}$$

$$Z = \frac{rF}{r + 1} \tag{5.12}$$

Now, substituting (5.11) and (5.12) into (5.9), we obtain (5.13), with the function defined in terms of a single fertilizer mix. Simplifying equation (5.13), we obtain (5.14), the type of equation used later for deriving marginal rates of substitution of fertilizer for land, when the fertilizer mix is that common to the location of the data.

$$Y = a + \frac{bF}{r + 1} + \frac{crF}{r + 1} - d\left(\frac{F}{r + 1}\right)^2 - e\left(\frac{rF}{r + 1}\right)^2 + f\left(\frac{F}{r + 1}\right)\left(\frac{rF}{r + 1}\right) \tag{5.13}$$

$$Y = a + \frac{b + cr}{r + 1}F + \frac{fr - d - er^2}{(r + 1)^2}F^2 \tag{5.14}$$

Equation (5.14) is still in the form of a "per acre" production function. To incorporate land into the production function, the method in equations (5.3) to (5.8) is used.

Labor Substitution

Since fertilizer also is a substitute for labor, the marginal rate of substitution of fertilizer for labor can be defined somewhat similarly. For purposes at hand, labor and land can be considered as technical complements, with k units of labor used per acre of land. (Under other formulations and aggregations, they are substitutes in producing food supply.) The increment of labor used to apply fertilizer and harvest the added yield is small for U.S. mechanized farming. Hence, land and labor here will be considered as fixed in the proportions L = kA or $A = k^{-1}L$ where L is hours of labor used and k is hours required per acre.[3] Substituting $A = k^{-1}L$ into equation (5.5), the production function

[3] We could compute substitution rates similarly if we supposed a quantity of labor L = kA as a "fixed requirement" per acre, but also considered the variable labor quantities L = f(F) and L = g(Y) where labor is respectively a function of fertilizer applied and per acre yield. However, since these are small quantities, we do not add the details here.

in (5.15) is obtained where output is a function of the amount of labor and fertilizer used, based grossly on simple experiments.

$$Y = ak^{-1}L + bF - ckL^{-1}F^2 \tag{5.15}$$

The isoquant equation of the gross marginal rate of substitution of fertilizer for labor is (5.16).

$$\frac{dL}{dF} = \frac{2ckL^{-1}F - b}{ak^{-1} + ckL^{-2}F^2} \tag{5.16}$$

Since labor and land are considered to be technical complements here, the labor quantities (5.15) and (5.16) are always associated with $k^{-1}A$ units of land.

Empirical Estimates of Substitution of Fertilizer for Land

As mentioned above, the substitution rates derived are not predictions of those which have existed in the history of U.S. agriculture. Instead, they represent substitution rates under the specific natural and environmental conditions of the data and thus refer to a specific set of physical potentials. The sample of functions is not necessarily typical or representative for the nation in respect to soils, weather and similar phenomena. Our purpose is not to predict for time and the nation, but to indicate potential fertilizer/land marginal substitution rates under particular conditions. In relation to bias in estimating substitution rates under actual farm conditions, the physical considerations discussed in Chapter 6 for static demand functions also apply here.

All estimates are for corn. Derivation of gross marginal rates of substitution are made for the following soil types, years and nutrients: (a) Iowa Clyde soils for K and P in ratio 1:2 as an average over 1950, 1953 and 1956; (b) Mississippi Experiment Station soils for N as an average for the years 1921, 1926, 1931, 1936 and 1941; (c) Kansas Verdigras soil for nitrogen in 1958; and (d) North Carolina Coastal Plain soils for nitrogen in 1957.[4] For convenience, only two isoquants are considered for each state and soil, both isoquants representing a yield level attainable on a single acre (but not restricted to an acre as a fixed input magnitude). The isoquant levels for each state and soils are those falling at the yield level (a) a quarter of the way up the production surface due to fertilizer response and (b) three-quarters of the way up.[5]

[4] In the order given, the basic production functions are reported in (a) Iowa Agr. Exp. Sta. Bul. 424; (b) Tramel, T. Fertilizer Response Functions at Stoneville, Miss. Ph.D. Thesis, Iowa State University; (c) Kansas Agr. Exp. Sta. Bul. 94; and (d) North Carolina Agr. Exp. Sta. Bul. 126.

[5] If an experiment shows a yield of 40 bushels without fertilizer but the experimental inputs carried yield to a maximum of 56 bushels, the response is 16 bushels. Hence, our first isoquant is at 40 + 4 = 44 and the second is at 40 + 12 = 52 (the first having 1/4 and the second 3/4 of response added to the constant).

An example of the empirical quantities is provided below where (5.17) is the production function, (5.18) is the isoquant and (5.19) is the equation indicating gross marginal rates of substitution from the Iowa data.

$$Y = 35.6A + 1.40F - .015A^{-1}F^2 \tag{5.17}$$

$$A = -.02F + .014\left[Y + \sqrt{2.147F^2 + (Y - 1.404F)^2}\right] \tag{5.18}$$

$$\frac{dA}{dF} = \frac{.030A^{-1}F - 1.404}{35.60 + .015A^{-2}F^2} \tag{5.19}$$

Similar equations were derived for the other three locations. The resulting data for isoquants and marginal rates of substitution are given in Tables 5.1 and 5.2. For a 33.8 bushel isoquant in Mississippi the isoquant is represented by the fertilizer quantities under F and the land quantities under A, starting with 1.13 acres. The Mississippi isoquant

Table 5.1. Isoquants and Gross Marginal Rates of Substitution Between Land (A) and Fertilizer (F) Nutrients for Iowa and Mississippi

Lb. F	Iowa				Mississippi			
	43.8 bushels		60.1 bushels		33.8 bushels		41.6 bushels	
	A	MRS	A	MRS	A	MRS	A	MRS
0	1.23	-.0394	1.69	-.0394	1.13	-.0171	1.39	-.0171
10	.88	-.0283	1.33	-.0323	.98	-.0138	1.23	-.0145
20	.69	-.0109	1.06	-.0204	.86	-.0095	1.10	-.0112
30	--	--	.92	-.0082	.79	-.0049	1.01	-.0074
40	--	--	.88	-.0005	.76	-.0016	.96	-.0038
50	--	--	--	--	--	--	.94	-.0010

Table 5.2. Isoquants and Gross Marginal Rates of Substitution Between Land (A) and Fertilizer (F) Nutrients for Kansas and North Carolina

Lb. F	Kansas				North Carolina			
	73.8 bushels		82.6 bushels		42.4 bushels		76.9 bushels	
	A	MRS	A	MRS	A	MRS	A	MRS
0	1.06	-.0045	1.19	-.0045	1.69	-.0302	3.06	-.0302
20	.98	-.0037	1.11	-.0038	1.11	-.0293	2.47	-.0287
40	.92	-.0027	1.04	-.0030	.68	-.0158	1.92	-.0258
60	.88	-.0016	.99	-.0019	.49	-.0043	1.45	-.0128
80	.85	-.0006	.96	-.0010	.45	-.0002	1.12	-.0063
100	--	--	.95	-.0003	--	--	.93	-.0025
120	--	--	--	--	--	--	.85	-.0005

for a 41.6 bushel yield is represented by the quantities under F at the left and under A, starting with 1.39 acres. The corresponding marginal rates of substitution (MRS) are in the columns. Similar isoquants, over their negative sloped portion, and MRS data for two yield levels are defined for each set of data.

A 42.4 bushel output is obtained for the North Carolina soil location with 1.69 acres of land and no fertilizer, 1.11 acres of land and 20 pounds of fertilizer, .45 acre of land and 80 pounds of fertilizer, etc. With the combination of 20 pounds of fertilizer and 1.11 acres of land for a 42.4 bushel output, a pound of fertilizer substitutes for .0293 acre of land. Hence, a ton of fertilizer nutrients spread similarly over more acres is estimated to substitute for 58.6 acres of land (i.e., 2,000 x .0293). With 60 pounds of fertilizer nutrients and .49 acre to produce 42.4 bushels, a ton of fertilizer nutrients substitutes for 8.6 acres of land. At the combination of 40 pounds of fertilizer nutrients and .96 acres to produce a 41.6 bushel output for the Mississippi data, a ton of fertilizer nutrients substitutes for 7.6 acres of land. For Iowa a ton of fertilizer nutrients substitutes for 56.6 acres of land when the combination is 10 pounds of nutrients and .88 acre of land to produce a 43.8 bushel output. However, when .88 acre of land and 40 pounds of fertilizer is used to produce a 60.1 bushel output, a ton of fertilizer substitutes for only 1.0 acre of land.

Corresponding differences also are obvious for other isoquant combinations which involve approximately the same land input (as 1.11 and 1.12 acres for the two yield levels of North Carolina). For the data shown in Kansas, the marginal rates of substitution vary from the equivalent of a ton of fertilizer for 9.0 acres of land (starting from zero fertilizer and 1.06 acres of land to produce a 73.8 bushel output) to a ton of fertilizer for .6 acre (100 pounds of fertilizer and .95 acre to produce an 82.6 bushel output).

Obviously, the gross marginal rate of substitution of fertilizer nutrients for land varies with the soil type, rainfall, crop, climate and other environmental factors — as well as with the ratios in which fertilizer and land are combined under any unique combination of these factors. As an average for all isoquant combinations of the four locations shown in Tables 5.1 and 5.2, the gross marginal rate of substitution of fertilizer nutrients for land is .0118 or a ton of nutrients for 23.6 acres of land. (This average of the MRS's has no weighted or predictive value, but is mentioned as a summary illustration.) The MRS value ranges from .0002 (a ton of fertilizer for .4 acre of land) with 80 pounds of fertilizer and .45 acre of land to produce 42.4 bushels of output in North Carolina, to .394 (a ton of fertilizer for 67.8 acres of land) starting at zero level of fertilization in Iowa. The rate at which fertilizer substitutes for land also varies with the level of fertilization of each acre of land.

As we mentioned previously, these are "gross" marginal rates of substitution in the sense that resources which complement fertilizer and land also are involved. For example, x tons of fertilizer which might replace z acres of land in meeting a given level of food requirement also would allow less machinery to be used for a smaller acreage. Less labor also would be required since a given output produced on fewer acres with a higher per acre yield requires less labor than the same output on more acres with lower yield. Hence, a single major factor seldom is substituted for a single other factor in agriculture. However, the "gross" marginal rates of substitution of fertilizer (as a technology and resource) for land are of importance or relevance. Given a favorable supply price for the "fringe" resources which complement either fertilizer or land, national policy or planning still is concerned about the rate and extent to which a major resource such as fertilizer can substitute for a "fixed" resource such as land.

Substitution of Fertilizer for Labor

Using average labor requirements per acre of corn as reported by the USDA for 1959, we now estimate marginal rates of substitution between fertilizer nutrients and labor. The marginal rates of substitution are obvious from previous equations and data. Here we refer to labor which is associated marginally with land, in the sense that if we replace an acre of land by fertilizing remaining acres at a higher level, we also displace the constant quantity of labor required to handle the "displaced" land. As a given output is produced by diverting some land from production and producing more on fewer acres at a higher yield, some of the displaced labor (attached to the displaced land) is offset by the added labor required to harvest and handle the higher yield on the remaining acres, as well as by some added labor for applying the fertilizer. However, under U.S. mechanized farming, the incremental labor to apply the fertilizer and harvest the greater yield is trivial and can be neglected in aggregative importance (or can be recognized in the sense that the substitution rates we present in Table 5.3 for Iowa and Kansas are slightly greater than the actual "net" rates).

Again the rates of substitution of fertilizer for labor depend on environmental conditions at each location, as well as the proportions in which labor and fertilizer are combined (i.e., the per acre rate of fertilization). With 20 pounds of fertilizer for the Kansas data, 5.60 hours of labor are required to produce 73.8 bushels, while 6.32 hours are required for 82.6 bushels. The corresponding marginal rates of substitution are 1 pound of fertilizer for .021 hour of labor in the former and .022 hour of labor in the latter case. Starting from zero level of fertilization for the Iowa data, 1 pound of fertilizer substitutes for .304 hour of labor. With 40 pounds of fertilizer and 6.78 hours of labor (and also the .96 acre of land in Table 5.1) to produce 60.1 bushels in Iowa, a pound of fertilizer substitutes for only .004 hour of labor. Put on the basis of the equivalent of a ton of fertilizer, these two extremes in Iowa represent the substitution of a ton of fertilizer for 608 hours and 8 hours of labor, respectively. In other words, at the first

Table 5.3. Isoquants and Marginal Rates of Substitution for Fertilizer Nutrients and Land for Iowa and Kansas Data

	Iowa				Kansas			
Lb.	43.8 bushels		60.1 bushels		73.8 bushels		82.6 bushels	
F	L	MRS	L	MRS	L	MRS	L	MRS
0	9.47	-.304	13.00	-.304	6.04	-.026	6.78	-.026
10	6.44	-.213	8.70	-.246	--	--	--	--
20	3.42	-.006	8.16	-.154	5.69	-.021	6.32	-.022
30	--	--	7.08	-.062	--	--	--	--
40	--	--	6.78	-.004	5.24	-.015	5.93	-.017
60	--	--	--	--	5.02	-.012	5.64	-.011
80	--	--	--	--	4.67	-.009	5.47	-.006
100	--	--	--	--	--	--	5.46	-.002

combination, a ton of fertilizer nutrients substitutes for 76 eight-hour days of farm labor. In the second case, on the "gross" basis described earlier, a ton substitutes for one day. For the Kansas data, the range is 6.5 to .5 days of labor replaced by a ton of fertilizer nutrients.

While the data above are for experimental conditions and may somewhat overestimate the rate at which fertilizer substitutes for land and labor, the marginal replacement rates obviously are high. Of course, as mentioned in earlier chapters, the individual farmer does not buy more fertilizer and use less land, as he might in the case of machinery and labor. He purchases the fertilizer and uses it on a given land area. In an aggregate sense and over time, however, fertilizer does become a substitute for these two resources (and their technical complements in producing an acre of crop) since the given output can be produced with fewer acres. Trends in the use of more fertilizer, connected with the substitutability for land, and government policies which kept land in production, contributed to surpluses and public stocks over the previous decade.

These rates are for corn and would not necessarily apply to a random sample of farms or to other crops and locations. Yet they illustrate the magnitude that substitution rates may take as a capital technology is substituted for land and labor. Other innovations or capital technologies serve as similar substitutes. For the United States, Thompson et al. estimated that 40 percent of the per acre increase in corn yield between 1940 and 1958 was due to improved seed and 34 percent to fertilizer.[6] On this basis, the capital associated with use of improved seed and fertilizer on one acre would substitute on the average for around .6 acre of other land. In other words, approximately 1.6 acres of land under the technology of 1940 was necessary to produce as

[6] Thompson, L. M., et al. Some causes of recent high yields of feed grains. Proceedings, Feed and Livestock Workshop. Center for Agricultural and Economic Development Special Report No. 24. Ames, Iowa. 1959.

much as one acre under the technology of 1956. Even if yields are discounted somewhat due to favorable weather in the latter year, these estimates would indicate that few pounds of improved seed and perhaps less than 30 pounds of fertilizer nutrients (and the capital used with them and in developing and supplying them) per acre substitute, in an average context, for .5 acre of land. In other terms, the use of 30 percent less land and 25 percent less labor than otherwise would have been necessary to produce the nation's 1958 corn output. To these substitution rates for capital which relate to feed grains must be added those which relate to livestock production. The increase in gain per bird or animal illustrated in Chapter 4 from various new capital technologies also allows a given output to be produced (since less feed is required) from a smaller input of land and labor. These substitutions take place in the farm production process, as a result especially of new knowledge defining the relative productivities and profits of the new capital forms.

Substitution of Water for Land

Table 5.4 indicates yield isoquants and marginal rates of substitution of water, W, for land, L, in production of corn. The left side of Table 5.4 is based on the judgment production function (5.20) for Colorado.[7] W is acre-inches of irrigation water but also includes fertilizer

Table 5.4. Isoquants and Gross Marginal Rates of Substitution Between Irrigation Water and Land for Colorado and Indiana

Inches of water	Colorado				Indiana			
	24.8 bushels		74.3 bushels		32 bushels		95 bushels	
W	A	MRS	A	MRS	A	MRS	A	MRS
3					.274	-.0687	--	--
4					.252	-.0000	--	--
5					.261	.0134	--	--
5.25	.258	-.0698	--	--				
5.50	.251	-.0108	--	--				
5.75	.250	.0035	--	--				
10					--	--	1.1733	-.2837
12					--	--	.9937	-.0267
14					--	--	.9742	.0017
16	--	--	.763	-.0357				
16.5	--	--	.752	-.0108				
17	--	--	.750	.0000				
17.5	--	--	.752	.0063				

[7] Whittlesey, Norman K. Valuing Irrigation Water in the Uncompaghre Project. Unpublished M.S. Thesis. Library, Colorado State University. Fort Collins. May 1960.

in amounts appropriate to make application of water feasible. The right side of Table 5.4 is based on production function (5.21) which was derived from an irrigation experiment on Fox Sandy Loam Soil, Sullivan County, Indiana, in 1956.[8] The stand and fertilizer levels were fixed at their respective means and W refers to acre-inches of irrigation water.

$$(5.20) \qquad Y = -203 + 26.64W - .5878W^2$$

$$(5.21) \qquad Y = -238 - 23.25W + 184.27W^{1/2}$$

The highly negative intercepts in (5.20) and (5.21) indicate that appreciable inputs of water are required to make Y greater than zero.

The isoquants and marginal rates of substitution in Table 5.4 are derived by the same steps outlined in (5.1) to (5.7). The relevant economic range, where the isoquants have a negative slope and the MRS is negative, is narrow for both areas. According to Table 5.4, inputs of water must be considerably greater than zero before the relevant economic range is approached because of the negative intercepts in (5.20) and (5.21). That is, neither land nor water can produce corn without the other input and the relevant land/water ratio is narrow. Output of 74.3 bushels of corn can be produced, for example, with 16 acre-inches of water and .76 acre of land in the Colorado location. The application rate per acre is 16/.763 = 21 acre-inches. Because of the properties of the production function (5.20), water must be applied at approximately this rate for maximum efficiency. The gross marginal rate of substitution of water for land when W = 16, A = .76 is -.0357. One hundred acre-inches of water substitute for 3.57 acres of land, or 1 acre of land substitutes for 28 acre-inches of water. If 17 acre-inches of water and .75 acre of land are used to produce 74.3 bushels of corn, an additional acre-inch of water does not substitute for any land.

The Indiana data show that 95 bushels of corn can be produced with approximately 1 acre of land and 12 acre-inches of water. When A = 1.17 and W = 10, the Indiana data show that 1 acre-inch of water will substitute for approximately 1/4 acre of land, i.e. MRS = -.28. Opportunities for substituting water for land diminish rapidly as with the Colorado data. The corn yield isoquant slopes upward when W = 14 and Y = 95 for the Indiana data.

Table 5.4, while not necessarily representative nor a random sample of production units, gives a crude indication of the potential corn production from irrigated acres. Nelson estimates that about 18 million acres of potentially irrigatable land remains in 17 Western States, and approximately 29 million acres in the East.[9] Although these acres conceivably could be irrigated if necessary, expansion of irrigation on

[8]Kadlec, John, Smith, LaVon and Niehouse, Ralph. Authors, Unpublished work sheets. Department of Agricultural Economics, Purdue University. Lafayette, Indiana. 1962.

[9]Nelson, L. B. Physical potentials for crop production. Chap. 8. In Iowa State Center for Agriculture and Economic Development. Dynamics of Land Use — Needed Adjustments. Iowa State University Press. Ames. 1961.

these acres is likely to come slowly, the actual rate depending on food prices resulting from population pressure and other sources. Under certain assumptions Nelson estimates that irrigated acreage in the West will be 11.2 million acres greater, in the East 4.7 million acres greater, by the year 2000. If, as implied by functions (5.20) and (5.21), this added land without water is unproductive but will yield 100 bushels per acre with from 15 to 25 acre-inches of water and appropriate fertilizer, the potential for increasing corn output is very great (roughly one-third of the current total corn output). However, the potentials thus derived may not be meaningful for the additional acreages because: (a) irrigation would need to be extended to units less suited and less responsive than the above to irrigation water, (b) the most limiting resource may be water and management, rather than land and (c) many of the added acres would be used for crops other than corn.

The foregoing estimates of yield isoquants and marginal rates of substitution indicate how technologies and capital such as fertilizer and irrigation water substitute for land and labor. The estimates characterize some of the changes which have already occurred in agriculture but also are indicative of sizeable opportunities for increases in output per unit of labor and land in the future.

All data indicate that opportunities for substituting capital and technology for conventional resources offer considerable future promise for further increasing the productivity of land and labor.[10] The foregoing estimates are largely normative, indicating what "could be." We now examine some aggregate measures of actual substitutions which have taken place in the resource mix of agriculture.

HISTORICAL SHIFTS AND SUBSTITUTIONS IN THE AGGREGATE AGRICULTURAL PRODUCTION FUNCTION

As mentioned in Chapter 3, broad estimates for the nation suggest that yield increases per annum for all crops in the United States over the last several decades came 10 percent from hybrid corn, 45 percent from fertilizer, 6 percent from irrigation and 37 percent from improved seeds, cultural practices and similar innovations. In majority these several sources represent new resources activated in the nation's agricultural production function for crops. In earlier decades the existence of many of these specific capital items was not known and the productivity coefficients of others were not yet established. In a rough manner these data suggest the rate at which knowledge of change in productivity coefficients have been communicated to farmers, and adopted by them. The rate of adoption of new resources is conditioned

[10] Estimates of future potential for increasing crop output from use of fertilizer and irrigation are found in Nelson, L. B. Physical potentials for crop production. Chap. 8; and Ibach, D. B. Economic potentials of agricultural production. Chap. 9. In Iowa State Center for Agriculture and Economic Development. Dynamics of Land Use – Needed Adjustments. Iowa State University Press. Ames. 1961.

by the institutional, psychological and economic restraints. New and improved inputs would not have been adopted had their supply price been prohibitive, but neither would they have been adopted had they or their productivity coefficients been unknown.

The entire physical production function, and knowledge about it, can be represented as in (5.22) where there are n possible resources of specific form. Each seed variety, for example, represents a different X_i, as does water at different times of the year, various types of machines, power, fertilizer, labor, soil type, etc.

$$(5.22)\ Y = f(X_1, X_2, \ldots X_g, X_{g+1}, \ldots X_h, X_{h+1}, \ldots X_k, X_{k+1}, \ldots X_n)$$

At one extreme are those resources represented by $X_{k+1} \ldots X_n$ the existence of which is not yet established. Fundamental research is required to establish them. In the next category are capital or material items $X_{h+1} \ldots X_k$ of which the existence is known but the productivity coefficients have not been established. Technical research is required to establish or extend knowledge of their productivity. Inputs included in the category $X_{g+1} \ldots X_h$ are those in which productivity is known and are used in the production process to the extent that their output coefficients and prices are favorable. In category $X_1, \ldots X_g$ are resources which have been released from the production process because their productivity is low relative to their own price and that of substitute resources. In the latter category are oxen power, open-pollinated corn, threshing machines and other resources of an earlier era in U.S. agriculture. The pricing structure is important in moving resources from the second to the first category of resources, but technical knowledge is basic in moving them from the fourth to the third and from the third to the second categories. Certainly this has been an extremely powerful force in causing the productivity of U.S. agriculture to grow as specific categories of resources have been substituted for others.

Data availability does not allow refined estimates of marginal productivities for all major new forms of capital developed in recent decades. Neither do we have aggregate production functions estimated over time which allow us to make "safe" predictions for broad aggregates of resources. From the production functions in Table 4.1 we can derive the estimate (from equation 4.1) that the marginal rate of substitution of operating inputs, Q_O, for real estate, Q_{RE}, increased from 1.04 in 1930 to 3.11 in 1959. While these are realistic substitution quantities in terms of the more specific examples cited in the previous section, we prefer to use more aggregative and less refined estimates based on other data.

The quantities in Table 5.5 show the annual inputs of resources for U.S. agriculture in 1910 and 1960. The last column shows resource requirements had the technology of 1910 been projected to 1960, with the output in the latter year composed of the same mix of outputs and produced with the same mix of inputs as in the former year. The 1960 output level is assumed, corrected slightly for weather (with 1960 output

Table 5.5. Annual Input Quantities, Resource Stocks and Employment, 1910, 1960 and 1960 Projected on 1910 Technology and Mix*

Annual input or resource	1910 Actual	1960 Actual	1960 Required With 1910 Mix and Technology
	(million 1947-49 dollars)		
Farm labor			
Value	15,016	6,866	30,783
Hours	22,547	10,310	46,181
Real estate	3,408	3,750	6,986
Machinery and power	1,109	5,557	2,273
Fertilizer and lime	166	1,561	340
Plant nutrients (1000 tons)	856	7,571	1,754
Livestock inputs	624	903	1,280
Crop inputs	379	623	777
Operating capital	116	306	248
Miscellaneous inputs	732	1,307	1,500
All inputs	20,643	25,292	42,318
Employment and physical stock (1947-49 dollars)			
Labor employment (mil.)	13.6	7.1	27.9
Horses and mules (mil.)	24.2	3.0	49.6
Tractors (1000)	1	4,780	2.1
Cropland (mil. acres)	330	356	677
Real estate (mil. $)	56,065	65,825	114,933

*USDA Statistics. For the general source, see Loomis, R. A., and Barton, G. T. Productivity of agriculture. United States, 1870-1958. USDA Tech. Bul. 1328. 1961. Taxes are included in all inputs. Without taxes, the quantities for all inputs are, respectively, for the three columns: 20,141; 23,987; 41,289.

equal to 2.05 times 1910 output). The same relative mix of inputs would be continued over time only if the production function were fixed and one with linear isoclines passing through the origin of input space, relative product and factor prices remained unchanged, the supply elasticity of factors remained constant among resource categories and consumer demand held commodities in fixed proportions in respect to quantities and qualities. None of these conditions has prevailed exactly, and they would not have even in the absence of economic development and a perfectly elastic land supply. Hence, the last two columns tend to distort changes in resource mix or structure which have occurred in comparison to those which would have prevailed in the absence of technological change. Despite this, the data generally do suggest absolute changes which have taken place in resource structure. Under the assumed conditions, the substitution of technologically improved capital for conventional input has resulted in "savings" of annual inputs approximating $17 billion. (The figures are perhaps conservative because the mix of products consumed has higher resource requirements than the commodity mix consumed in 1910.) If we take the differences between the last two columns as a basis of comparison of "increments" and "decrements" to produce the 1960 output, the data show that $10,380 million in annual machinery, power (4.6 million tractors), fertilizer and lime, and operating inputs substituted roughly and in aggregate for an annual input of $193 million in miscellaneous inputs, 20.8 million persons employed, 347 million acres of cropland, 46.6 million horses and mules and $49,108 million of physical real estate stock. Or, the $10,380 million in annual inputs of the first category substituted for $27,817 million in annual inputs of the second category. (The "increments" and "decrements" again are comparisons between columns 3 and 4.) Even discounted to a quarter or a half of these quantities, the magnitudes of substitution have been large and it has been possible to effectively save much labor, land and farm-produced capital through extension of the first category of inputs.

Without change in technical knowledge, the resource mix would not have remained at the 1910 proportions. For one thing, the supply price of factors would have changed relatively. Land with a low supply elasticity would have increased greatly in price and substitutions would have been made through fertilizer, higher seeding rates, more intense applications of labor, irrigation developments and similar extensions of conventional inputs in the context of a given knowledge and production function. Output also would have been lower, with a higher price for farm commodities and absence of surplus stocks. Even extension of inputs with a given production function would have caused the proportions of resources to change from the 1910 standard since the isoclines of the aggregate production function in agriculture are not linear through the origin. A likely hypothesis is that the configuration of this isocline would have taken the input mix proportionately more in the direction of fertilizer and irrigation capital, and less in the direction of farm machinery, nonfarm energy, general operating inputs and buildings. (This is comparison with the 1910 mix projected to 1960 under implied assumptions of linear isoclines through the origin of the input plane.)

In this chapter we have shown some substitution rates among resources as they relate to some highly micro relationships, resource categories and samples, and to some highly aggregated categories for the over-all farm sector.[11] The estimates are examples of substitution potentials in agriculture. They do not explain the behavior of farm entrepreneurs in demand for resources relative to changes in explanatory variables. In later chapters we estimate demand for numerous

[11] With more success in formal estimation of aggregate time series production functions such as those attempted in Table 4.1, we could similarly derive static aggregate factor demand and product supply relations. For the numerous reasons discussed elsewhere (multicollinearity, data and specification biases, changes in factor form and quality, etc.), we are not able to do so with any reasonable degree of reliability.

aggregates of resource inputs in relation to factor prices and imperfect indices of technical change. However, before we examine these, we now turn to estimates of static factor demand and product supply functions and elasticities based again on a restricted sample of data and resource categories. We make these specific examinations, partly to offset the "overly broad" categories and aggregate relationships of later sections but more particularly to provide knowledge of potential factor demand elasticities and conditions as they relate to a restricted type of physical production function. As is illustrated elsewhere in this study, farmers' resource demand response rests not only on technical coefficients but also on prices, objective functions, psychological settings, equity position and others.