Efficiency of energy use in producing maize with different technologies

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Introduction

Sunlight, fossil fuels, and the labor of man and beast are the major sources of energy for crop production. Sunlight provides the energy for the biochemical processes that reduce carbon dioxide in the air to carbohydrate in the crop. But, only a small portion of the energy available from sunlight is conserved in photosynthesis -- the majority escapes as heat.

In addition to sunlight, the production of food, feed and fiber is supplemented by cultural energy. This energy comes from human and animal labor, fossil fuels burned by tractors and vehicles during cultivation and harvesting, and energy used in transportation and in processing. Cultural energy also includes all energy required to grow seed, construct buildings, and to produce machinery, chemicals and fertilizers. A small part of the cultural energy is conserved when the crop utilizes plant nutrients from fertilizers, but most is ultimately dissipated into the environment as heat, not transformed into harvestable energy.

This paper evaluates cultural energy efficiency for both developing and advanced corn production systems by comparing the input of human and animal labor and supplemental sources of energy with the caloric yield of the crop.

Procedure

Efficiency. The usual definition of efficiency is the ratio of useful output of energy to the inputs of energy. This measures how completely the inputs are transformed into the outputs. It was noted earlier, however, that practically no cultural energy is transformed into plant tissue, therefore the usual definition is not applicable.

Farmers invest calories of energy in tillage, fertilizers, pesticides, irrigation, harvesting, and processing to help crops convert calories of sunlight into calories that man or animals can digest. Calculating the caloric gain, or the ratio of calories of yield to the investment of calories of cultural energy (cal cal^{-1}), for specific cropping systems reveals whether the investment has multiplied, remained static, or declined. Caloric gain will be considered as a measure of the efficiency of utilization of cultural energy. Thus, by contrasting caloric gain among cropping systems, the comparative efficiency of the utilization of cultural energy is revealed.

Cropping Systems

Eleven agricultural systems were selected for analysis. These systems included five levels of the application of technology to corn production; primitive swidden agriculture based upon human labor, less primitive corn culture relying upon human and animal labor, corn culture during the transition from animal labor to the internal combustion engine, corn production during the adoption of hybrid corn, and corn production in modern agriculture.

Primitive and Developing Agriculture. Four of the systems are comparatively primitive. In Cases 1-3, human labor is the sole cultural energy. Oxen supplement human labor in Case 5. Few metal implements made with fossil fuel are employed in these four systems. For primitive agriculture, an account estimate of the expenditure of energy by man and beast appears to be an acceptable estimate of cultural energy.

Case 4 exemplifies a type of developing agriculture where a primitive maize culture employing human labor is supplemented with cultural energy from chemical insecticides and vehicular transport. Thus, in addition to human energy, the analysis must account for the fossil fuel needed to manufacture insecticide and provide vehicles.

Transition agriculture. Three agricultural systems are typical of corn culture in the United States between 1910 and 1920 (Cases 6, 7, and 9). During this period, animal labor and metal implements supplemented human energy. Energy used to construct and maintain buildings, to house draft animals, to make machinery and implements and to store crops, is all classified as cultural energy.

Both coal and gasoline were used to fuel stationary engines powering forage cutters to produce corn silage, while the other two systems studied were the prevalent methods of producing grain at the time. In one of these, the corn was shocked before removal of the ear, while in the other, the ear was harvested from the standing plant. Energy expended by man and draft animals completes the estimate of cultural energy.

Adoption of hybrid corn. One agricultural system (Case 8) is typical of corn culture in the United States in 1938, when hybrid corn had been adopted by about half of the farmers in the Corn Belt. In 1938, tractors and other machines were the major source of cultural energy. Human energy was required to operate machines, but the use of animal power was declining. Practically no commercial fertilizers or pesticides were being used. Thus, in addition to human energy, the analysis must account for the fossil fuel used in farming operations and energy needed to construct buildings, and make implements and vehicles.

Modern agriculture. In 1969, tractors and other machines were the major source of cultural energy (Cases 10 and 11). Human energy was required to operate machines, but animal power had become obsolete. Thus, in addition to human energy, the analysis must account for the fossil fuel used in farming and processing operations and energy needed to construct buildings, make implements and vehicles and to produce fertilizers and pesticides that are characteristic of advanced agriculture.

Since buildings, implements and tractors and other vehicles are used for many years, estimates of depreciation were used to prorate the energy needed to produce them for both transitional and modern agriculture

Cultural Energy

Cultural energy was calculated from the expenditure of human and animal energy in agricultural operations and from crop production costs itemized in farm records. Cost records for specific crops reveal the variable and fixed costs associated with crop production. Fixed costs include depreciation of equipment, insurance, taxes, and interest, while variable costs include fuel, seed, fertilizer, lime, feed, repairs, rented equipment, and labor. Insurance, taxes, and interest were not translated into energy in this study. Estimates of the expenditure of cultural energy were made from information about variable and fixed farming costs. For primitive agriculture, there were no identifiable fixed costs. The variable costs were the hours of human and animal labor required to grow the crop.

For each crop, the human labor expenditure in hrs acre^{-1} was converted to energy at the rate of 175 kilocalories (Kcal) hr^{-1}. When draft animals such as horses or water buffalo were used, animal labor was converted to energy at the rate of 2,400 Kcal hr^{-1}. The heat of combustion of coal used to fire steam engines in 1910 to 1920 was about 6,650 Kcal kg^{-1}. Cost accounts list the gallons of gasoline or diesel fuel at \$0.28 gal^{-1}, and to energy at 32,000 Kcal gal^{-1}.

Value of Energy

After converting the labor and fuel consumed in production to energy, the dollar value of seed, fertilizer, lime, herbicides, insecticides, custom hire of equipment and depreciation of the physical plant remained. All are sources of cultural energy for crop production, but the energy and labor required for their production are not easily assessed.

Since production of goods and services in commerce consumes energy, the following model was used: The annual consumption of energy from mineral fuels was related to the gross national product in current dollars, and the consumption of energy accompanying the production of a dollar or goods and services was calculated for 1900 to 1970 (Fig.1). By using the value of energy as dollars of goods and services, dollars were translated into energy without explicit knowledge of the portion of the cost of machinery, fertilizer, herbicides, or depreciation that was directly attributable to the consumption of fossil fuel, other sources of energy, or to labor. About 100.6 megacalories (Mcal) (1 megacalorie ≅ 10^6 calories) were consumed to produce a dollar of godds and services in 1915, a value which was used to translate current dollars into energy for the period between 1910 and 1920. In 1938, about 62.6 Mcal $dollar^{-1}$ were consumed in producing goods and services. In 1970, about 17.4 Mcal $dollar^{-1}$ were used to produce goods and services.

Energy in Crops

The energy content of the economic yield of a crop, i.e. the fraction of the dry matter production consumed by man or livestock, was calculated as digestible energy. Budgets of cultural energy and yield for the eleven cases are given in Table 2.

Results and Discussion

Cultural Energy and Yields of Digestible Energy

Yields of digestible energy were low, ranging from 400 to 2600 Mcal $acre^{-1}$ yr^{-1} in the primitive agriculture of Gambia, Ghana, and Mexico where cultural energy was derived exclusively from man (1, 2, and 3, Fig. 2). Among these three primitive systems, increases in human effort greatly stimulated digestible energy yields.

Supplementing human labor in privitive agriculture 300 to 2400% with cultural energy from draft animals failed to stimulate yields of digestible energy (5, Fig. 2). This comparison is particularly appropriate between 3 and 5 (Fig. 2), since the different types of culture were practiced by the same village. Similarly, supplementing human labor in primitive maize culture 22 to 600% with cultural energy from chemical insecticides and vehicular transport failed to increase yield compared with cultural practices using human or animal energy (3, 4, and 5, Fig. 2).

Yield of digestible energy rose when machinery was combined with draft animals to supplement the labor of man, and the three cases that are typical of maize production during the early 20th century in the United States exemplify this response (6, 7, and 9; Fig. 2). During this period the expenditure of 50% more cultural energy to produce silage rather than grain more than doubled the yield of digestible energy because practically all of the plant was harvested for animal feed.

Between 1915 and 1938, tractors replaced animals and stationary engines as the principal sources of cultural energy in crop production, but mineral fertilizers, herbicides, and pesticides were not in use. The 21 to 73% increase in the use of cultural energy, and the adoption of hybrid corn, nearly doubled the yield of digestible energy from grain compared with production in 1915 (6, 7, and 8; Fig. 2).

Modern maize production in 1969 required 5000 to 6000 Mcal acre^{-1} yr^{-1} of cultural energy, or nearly twice that required in 1938 and nearly three-fold that required in 1915. The greater yield of digestible energy in modern agriculture occurred when the cultural energy of fertilizers, herbicides, and pesticides supplemented that of man, machines, and hybrid corn in 1938, or that of man, beast, and machines in 1915. The 165% increase in use of cultural energy between 1915 and 1969 was accompanied by a 198% increase in the yield of digestible energy from grain (6, 7, 10; Fig. 2). Furthermore, the 66% increase in yield of digestible energy from grain between 1938 and 1969 accompanied an 86% increase in comsumption of cultural energy (8, 10; Fig. 2). Similarly, the 63% increase in yield of digestible energy from silage accompanied an 83% increase in the use of cultural energy between 1915 and 1969 (9, 11; Fig. 2).

Among the five levels of application of technology to maize production, systems using cultural energy from machines, machines and draft animals, hybrid corn, fertilizer, herbicides, and pesticides responded with increased yields of digestible energy compared with primitive agriculture. Moreover, progressively greater yields of digestible energy accompanied the investment of cultural energy in cases 6 to 11 (Fig. 2). Applying cultural energy from animals or from vehicles and pesticides to primitive agriculture using human labor failed to stimulate yields (1 to 5, Fig. 2).

Caloric Gain and Efficiency

Now we can appropriately inquire whether the cultural energy expended in producing a crop is returned as digestible energy for consumption by humans or animals. Prior to the use of machines and fossil fuels, yields were small, and 18 to 21 calories of digestible energy were accrued per calorie of cultural energy spent in maize production (1, 2, and 3; Fig. 3).

When cultural energy from pesticides and vehicles was applied to primitive maize culture employing human labor, the gain of the cropping system fell to about 15 because the added energy was used less efficiently (4, Fig. 3). Supplementing human with animal labor in primitive corn production reduced the caloric gain to 4 because the investment of additional cultural energy failed to increase yield (5, Fig. 3).

When machines were teamed with draft animals in transition agriculture, increased yield accompanied the increased expenditure of energy, and the gain of the maize production systems ranged from 3 to 6 (6, 7, 9, Fig. 3). Interestingly, the Iowa farmer of 1915 produced digestible energy about 2.5 fold more efficiently than his contemporary in Pennsylvania. Whereas the Iowa farmer shucked his maize directly from the stalk into the wagon, the Pennsylvania farmer initially bundled the plants into shocks before spending more energy to remove the ear from the stalks.

By 1938, tractors had replaced draft animals as the principal source of energy for tillage, and the investment of energy in grain production had increased by 42%. The development and adoption of hybrid corn both accompanied and contributed to the increased investment of cultural energy. The resulting yield increases gave a caloric gain of 4.9 that was similar to the efficiency of grain production 23 years earlier (6, 7, 8; Fig. 3).

In modern maize production, extensive mechanization and use of fertilizers, herbicides, and pesticides since 1938 has nearly doubled the investment of energy in grain production. Increased yields accompanied energy consumption to return 4.4 cal cal^{-1} in 1969 compared with 4.9 cal cal^{-1} in 1938 (8, 10; Fig. 3). A near doubling of the yield of digestible energy from silage accompanied a similar increase in energy spent for production between 1915 and 1969. Thus, silage returned 5.9 cal cal^{-1} in 1915, and 5.3 cal cal^{-1} in 1969.

In primitive maize production, the yields of digestible energy were small but the caloric gains of the cropping system were large because the cultural energy was used very efficiently. Efficiency of energy use declined when primitive systems were supplemented with draft animals or with vehicular transport and pesticides.

During the early 20th century, in the United States, the labor of man and beast was supplemented with fossil fuels. The yield of digestible energy rose compared with more primitive agriculture, but the caloric gain decreased because the supplemental energy was used less efficiently. Similarly, greater yields of digestible energy accompanied mechanization in 1915 compared with culturing maize by man and beast, but the caloric gain changed little.

Maize culture in 1938 and modern production derived practically all their cultural energy from fossil fuels or from other energy that replaces labor. Nevertheless, the efficiency of using energy in grain and silage production has changed little over the past half century. Intensive cultivation, fertilizers, machines, and hybrid corn permit maize to be produced as efficiently in 1969 as in 1915 because yields have kept pace with greater use of energy.

Table 1

Case	Location, Date	Source of Cultural Energy	Reference
1 (corn grain)	Gambia, 1953	man	3
2 (corn grain)	Ghana, 1947	man	2
3 (corn grain)	Mexico, 1944	man	5
4 (corn grain)	Colombia, 1971	man + machine	6
5 (corn grain + fodder)	Mexico, 1944	man + beast	5
6 (corn grain)	Iowa, 1915	man + beast + machine	4
7 (corn grain)	Pennsylvania, 1915	man + beast + machine	4
8 (corn grain)	Indiana, 1938	man + machine	1
9 (corn silage)	Iowa, 1915	man + beast + machine	4
10 (corn grain)	Illinois, 1969	man + machine	4
11 (corn silage)	Iowa, 1969	man + machine	4

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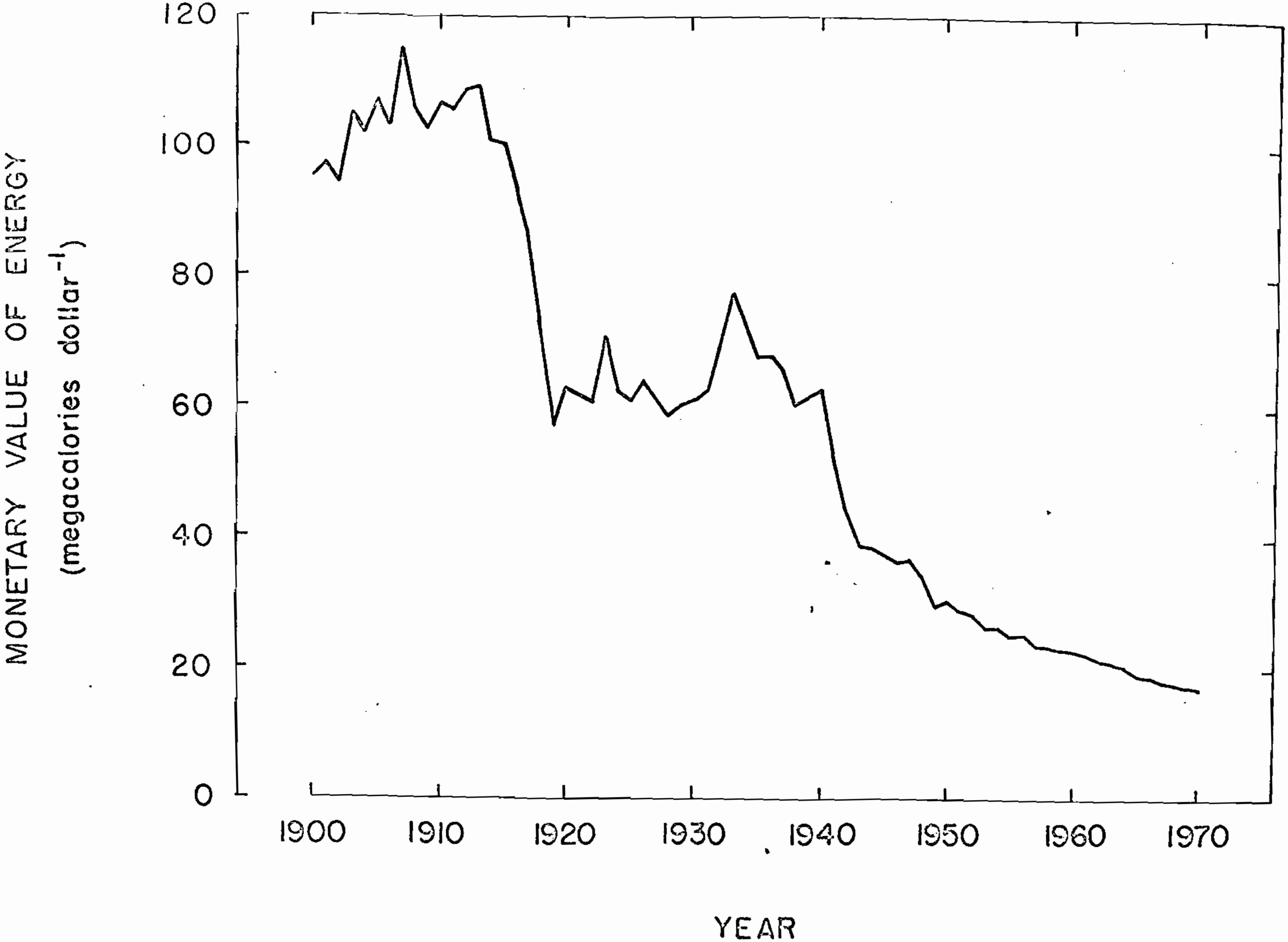
Fig. 1



References for Table 1

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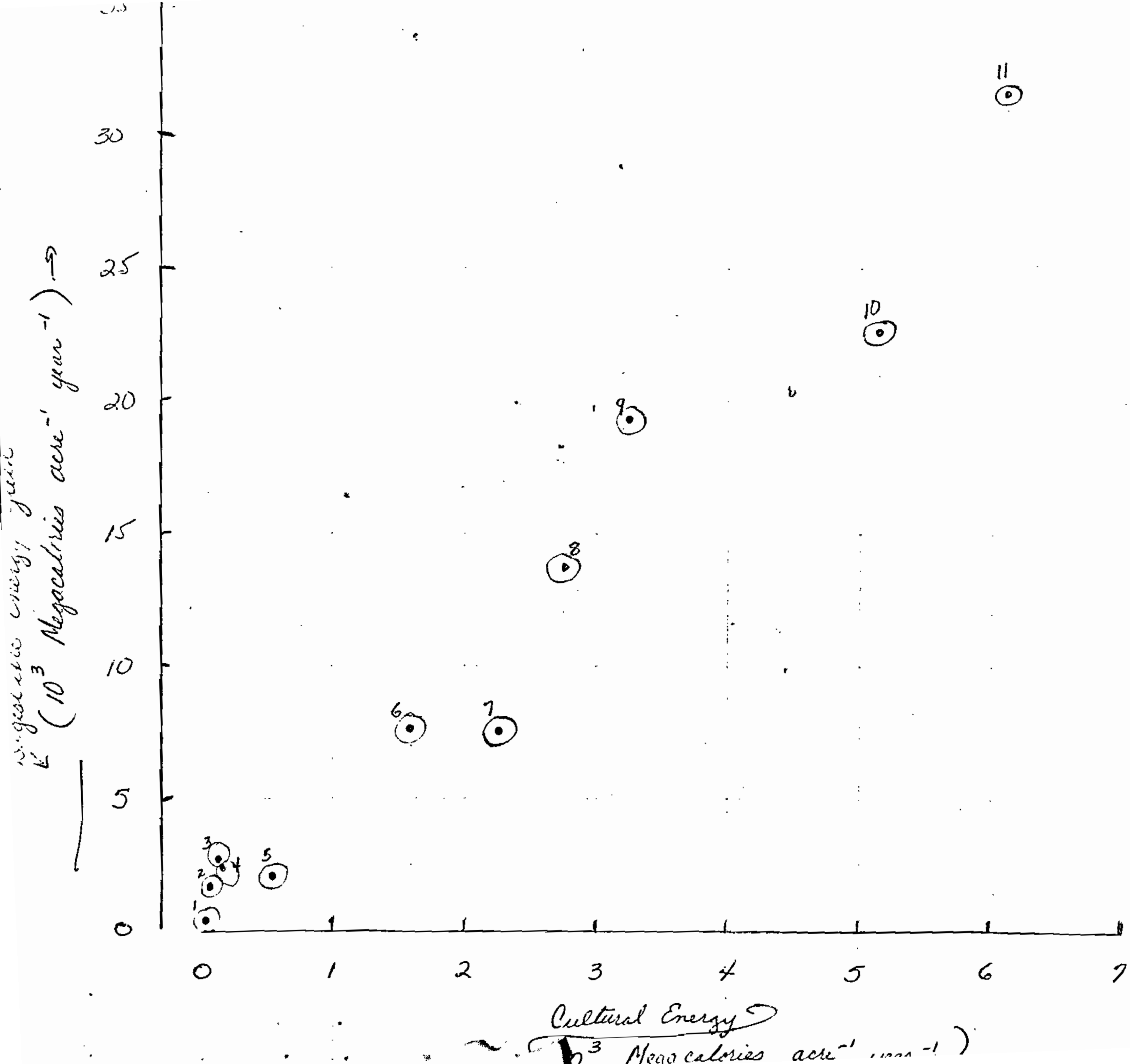
Fig. 2



(10³ Megacalories acre⁻¹ year⁻¹)
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
0
1
2
3
4
5
6
7
Cultural Energy

Digestible Energy Yield / Cultural Energy
(comparative efficiency)

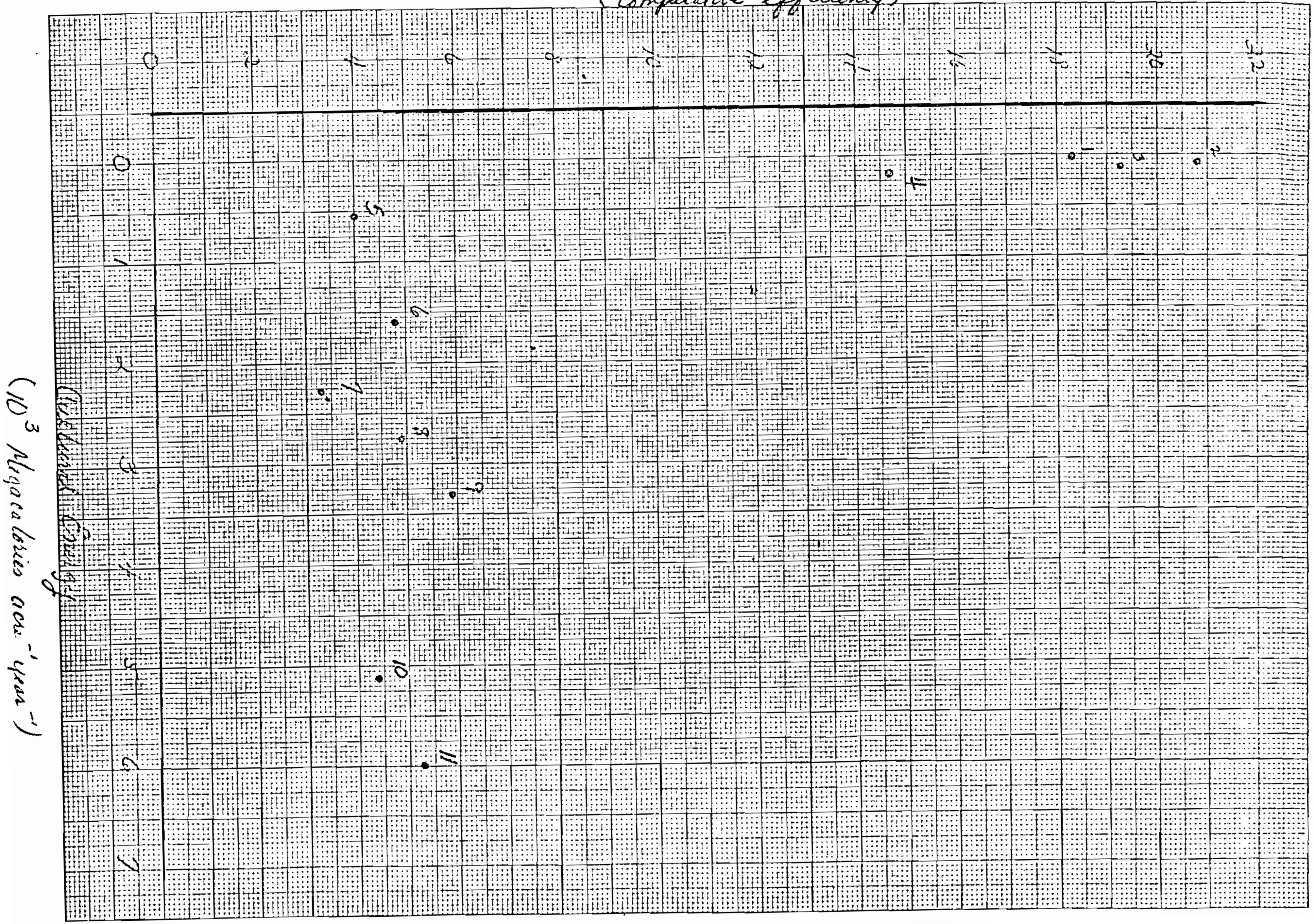


Fig. 3

Table 2

		Case				
Energy Input	Units	1	2	3	4	5
Labor - human	Mcal $acre^{-1}$	5.57	38.3	91.1	25	24.5
Labor - animal	Mcal $acre^{-1}$					24.9
Fuel	Mcal $acre^{-1}$				99.6 (Fuel, Other variable costs, Fixed costs)	
Other variable costs	Mcal $acre^{-1}$					
Fixed costs	Mcal $acre^{-1}$					
Total Cultural Energy						
Seasonal	Mcal $acre^{-1}$	5.57	38.3	91.1	124.6	273.5
Annual	Mcal $acre^{-1}$ yr^{-1}	22.3	76.6	136	166	547
Yield						
Growing season	yr	0.25	0.5	0.67	0.75	0.5
Economic yield	kg $acre^{-1}$	290	228	500	520	250 kg $acre^{-1}$ grain 200 kg $acre^{-1}$ fodder
Digestible Energy	Mcal $acre^{-1}$ yr^{-1}	408.3	1602	2627	2440	2160
Digestible Energy/Cultural Energy	cal cal^{-1}	18.3	20.9	19.3	14.7	4.0

6	7	8	9	10	11
3.0	8.8	1.5	4.9	0.95	1.8
105.4	129.6		124.6		
		362	131.9	800	1024
66.4	61.4	319	79.5	541	430
352	553.3	228	744.4	353	530
527	753.1	911	1085	1695	1986
1596	2282	2761	3289	5136	6018
0.33	0.33	0.33	0.33	0.33	0.33
711	711	1280	6909	2120	11270
7584	7584	13651	19389	22612	31624
4.8	3.3	4.9	5.9	4.4	5.3