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Problems of Power: Modification Versus Innovation [and Discussion]

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Problems of power: modification versus innovation

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In comparison with the amount of energy supplied by solar radiation for crop production, the amount of energy supplied by mechanical means is relatively small. The importance of the mechanical energy supplied by tractors and machines lies in its contribution towards the control of the growth process. The main trend in mechanization is for tractors and machines to become bigger and more powerful which in the farm structure of Western Europe leads to a mismatch between the capacity of the machines and the size of farms.

Modification is regarded as more likely that innovation. Modifications in design, management and farm structure are discussed. The principal challenge of innovation is seen as the one of scale in the use of power. A small tractor using a degree of automatic control is proposed for the 15 to 100 ha farms which form the majority of holdings in the E.E.C. Automatic feeding and recording systems for livestock units on such farms are also proposed.

1. Introduction

At the risk of over-simplification, an agricultural production system may be regarded as one with two types of input – energy and control. The energy inputs include such quantities as solar energy, water, land, fertilizers, machines, seeds and livestock. The control inputs are in the form of breeding, husbandry and management. Looked at in this way the magnitude of the solar energy contribution is so great that it dwarfs all the others and imposes a pattern on the production process that determines to a large extent the strategies for control which we can attempt to apply. The temperature – light constraint on plant growth determines almost completely our attitude to planting and cultivation and gives rise to the peaked pattern of agricultural production, especially in conditions of single cropping.

From a consideration of the overall thermodynamic efficiency of plant growth, it still seems true 'that whoever could make two ears of corn or two blades of grass to grow upon a spot of ground where only one grew before would deserve better of mankind . . .'. There is room for further improvement in the efficiency with which solar energy is converted to carbohydrate material through:

(i) Modification of the plant as a converter of solar radiation in order to increase yields per unit area.

(ii) Modification of the planting sequence in order to improve the overall annual efficiency of photosynthetic conversion through better organization in the use of existing resources. Multiple cropping is an obvious example of such an improvement. Small improvements in the utilization of sunlight are possible through earlier planting dates, which in Britain is likely to become an important factor in the management of both cultivating and planting machinery.

(iii) Better control of the growth of plants through additions of energy in the form of fertilizer, an adequate supply of water and reduction of competition from weeds and insects.

A characteristic feature of agricultural production is the seasonal period of harvesting which is a direct consequence of the dependence of production on solar radiation. Most crops are harvested at one period in the year, so that a seasonal peak of production must be matched with a demand that is relatively uniform during the whole year. This means that a large element of storage must be built into agricultural production – distribution systems in order to match demand with supply.

Seasonal production also raises special problems in the design and utilization of agricultural machines in that the demand for a machine is restricted to short intervals separated by long periods of idleness. Of course much of the early demand for mechanization was to reduce the need for extra temporary labour at times of planting and harvesting. There was a period of farm planning when the objective was to balance machinery and labour needs in order to maintain fairly constant employment over the whole year; more recently specialization in production in many cases has unbalanced labour demand.

2. Statistical trends in mechanization

In all countries of Western Europe a dominant trend of the 1960s has been a gradual reduction in the number of agricultural holdings with a correspondingly slow increase in the average size of farm. It is the small farms which disappear at the fastest rates; beyond a certain size, which varies from country to country – but is about 30 to 40 ha – the number of farms shows a marked ability to survive. However, by comparison with the North American pattern, the average size of Western European commercial farms is very small as shown in table 1.

Table 1. Average size of commercial farms 1967 (hectares)

Canada	207	Netherlands	16
U.S.A.	212	Belgium	11
Norway	13	France	24
Finland	19	German Fed. Rep.	10
Sweden	17	Austria	16
Denmark	20	Switzerland	16
United Kingdom	68	Italy	7
Ireland	16	Greece	3.3

Source: O.E.C.D.

In the application of power to agricultural production, the influence of the North American tractor and machinery market and of the large farms in Western Europe has had a distorting effect, in that the market forces have geared developments towards a farm structure which is not representative of conditions generally in Western Europe.

In all the industrial countries, the labour force in agriculture declined in the 1960s. This trend is likely to continue because in those countries there is a gap in incomes between workers in the industrial and agricultural sectors which acts as an inducement for workers to leave agriculture. There is also an inducement for farmers to replace labour by machines in an attempt to maintain production costs; of the major groups of agricultural inputs the factor costs of labour are rising at a faster rate than that of machinery.

The reduction in the number of workers and the consolidation in the number of holdings has lead to an increase in the number of tractors and associated machinery as shown in table 2.

While in the case of the U.K. and the U.S.A., the number of tractors on farms has remained stable, there has been an increase in the amount of power available because old tractors have been replaced by ones which are more powerful, sophisticated and effective. The very rapid increase which has taken place in Germany and France is a reflexion partly of the mechanization of agriculture and partly of the problems of providing tractors for small farms.

There is a tendency in Western Europe to compensate for the shortcomings of the prevailing structure of farms through specialization in production, which may be at the expense of the employment prospects or the crop rotation. There are various indirect forms of integration through contracting arrangements by processing and trading companies and new forms of cooperation under the name of 'group agriculture'.

Table 2. Number of tractors per 100 ha arable land

	1950	1960	1970
U.S.A.	2.0	2.5	2.7
United Kingdom	4.5	5.5	4.7
German Fed. Rep.	1.9	11.0	16.3
France	0.7	3.5	7.0

Source: *F.A.O. Production Yearbook*

3. Modification or innovation

A glance at the historical development of agricultural machinery shows that modification has been a much stronger theme than innovation. Most of the production operations are traditional and the machine elements for carrying them out have been evolved over a long period. Introduction of the tractor was met mainly by modifying existing equipment through increasing its strength and combining different operations to use the extra power which the tractor provided.

On the other hand, innovation changed the direction of well-established practices in a way which cannot be easily achieved with modification. The important innovations have been Bell's reciprocating mower, McCormack's reaper, Ransomes's chilled cast-iron plough share and Ferguson's draught control system.

Taking account of the present trends in machinery development in the E.E.C. and particularly in the U.K. some of the most likely modifications influencing productivity in the 1980s are as follows.

(*a*) *Modification of machines*

The most obvious trend in machinery development is an increase in the power rating of machines which is favoured by the relative cheapness of engines and encouraged by the need to raise the labour productivity of the operators especially on the large farms during the periods of planting and harvesting. If we retain the traditional methods of cultivation by mouldboard ploughs and tined implements, it is likely that 150 kW (200 hp) tractors will be widely used within 10 years. This development is likely to be accelerated by the demand for improvements in the working environment for the driver by protecting him from noise and vibration. Such isolation of the driver will not be cheap but the cost will be absorbed more readily in a large tractor than in a small one.

Improvements in the ergonomics of tractors would make possible work at higher speeds of travel and provide an escape from the present trend for ploughs, cultivators and other trailed machines to increase in width in order to match an increase in power in the tractor. Raising the speed of ploughing, for example to 12 km/h, would improve the power/weight ratio of a tractor, which in turn may off-set part of the cost of providing a better cabin for the driver.

Raising the speed of working to 12 km/h would mean considerable modifications in the design of mouldboards but little change in cultivators, and require development of seeding mechanisms which combine precision and reliability. Our understanding of the mechanics of soil movement on existing mouldboards is sufficiently good to allow us to generate the new shapes that would maintain the present quality of work at higher speeds (O'Callaghan & McCoy 1965).

Combine harvesters are now so wide that any further increase in the working width can only lead to marginal increases in the rate of working. However, it will require considerable re-design to get higher working rates by increasing the rate of forward travel: the header should be narrow to follow the ground terrain and should be automatically controlled to maintain a steady flow of material to the threshing drum; it should also reduce grain losses below the present levels.

Grass conservation, by hay or silage, involves a field drying operation. Rate of working is extremely important, partly to handle the large quantities of material and particularly to make the best use of atmospheric drying conditions. The capacity of cutting and conditioning machinery has only begun to exploit the amount of power which is available in the tractor so that we are likely to see further improvement in rates of cutting, tedding and baling. Rising fuel costs and greater concern with energy utilization should concentrate attention on field drying rather than thermal drying.

(*b*) *Modifications of machine management*

As machinery and labour become expensive more attention must be paid to its utilization and to unit costs. Already machinery accounts for a large proportion of the fixed asset formation in many European countries as shown in table 3.

TABLE 3. COMPOSITION OF GROSS FIXED ASSET FORMATION IN AGRICULTURE, 1967 (% OF TOTAL)

	farm buildings	land improvement	machinery
U.S.A.	21 (combined)		79
United Kingdom	40 (combined)		60
France	23	—	77
German Fed. Rep.	36	—	64
Netherlands	43	6	51
Sweden	17	8	75

Surveys of farm machinery usage show that farmers are not achieving the work rates claimed for the machines. The reasons are partly ergonomic in that some machines impose demands on the operator which he could not be expected to sustain over a whole working day, and partly a lack of training for the operator in using the machine. Many machines (e.g. forage harvesters) work as part of a system and their work rate is reduced to the lowest rate of material handling in the system.

In the management of machinery, modifications are possible both by a better organization of machinery systems and by a better understanding of the interaction between the economics of machine usage and crop production. The techniques of operations research, and especially simulation, are useful in understanding such problems and proposing solutions. Four of the problems which we have examined at Newcastle are:

(i) *Organization of high temperature grass drying*

The objective of grass drying is the maximization of profit from a resource of land and machinery. The output from the land can be controlled to some extent by selection of species and application of fertilizer, while the yield for sale is a combination of quantity of dry matter with a premium for quality in the form of protein content. There is also the organization of such factors as cutting, transport and utilization of the dryer. By setting up a linear programming model of the production and processing elements of the system an 'optimum' strategy was proposed.

The model emphasizes the importance of harvesting grass with a high protein content; in fact when the protein content falls below a certain level, depending on processing costs and the prices of competitive feeds, the advice from the model is that it is not economic to dry such grass and that it should be conserved as either hay or silage. The principal difficulty in the management of a high-temperature grass-drying plant is the one of reconciling equipment for processing which has a fixed capacity with a pattern of grass growth, which is seasonal, reaching a peak of production in early June. If the capacity of the plant is sufficient to deal with the maximum grass production, then the capital investment in equipment is too high in relation to the annual throughput. With the aid of the model it is possible to suggest strategies for the intervals between successive cuts, for a fertilizing policy to influence the natural growth pattern of the grass in the most profitable way, and for selecting a succession of different crops which could extend the drying season.

The model has been extended to interface the production of feed with the fattening of ruminant animals. In this way it is possible to use the results of animal feeding experiments both to formulate a ration based on a number of constituents and to define the time for harvesting a grass crop.

Mathematical models of production problems offer good possibilities for examining the interactions between different parts of the process and for devising optimum strategies for managing the complete process.

(ii) *Field emergence of sugar-beet seeds*

Germination of sugar-beet seeds in the field takes place during the transitory warming-up of the soil in spring. The problem is to examine the effect of cultural practices on the heat exchange properties of soil and to estimate the cost benefit of investment in machinery in relation to the expected gains in yield which result from early planting.

A simulation model based on actual weather records and on laboratory studies of the effect of temperature on the rate of germination of different strains of seed has been used to predict the emergence which might be expected from sowings made at various dates. Where the reliability of a model can be established by comparison with field trials, the model can be used to replace some field experimentation with considerable savings in costs and an increase in the amount of information which can be extracted about the system. In relation to the problems of sugar beet mechanization, the model can be used to explore the value of using different planting dates and the variations which can be expected between one area and another.

(iii) *Matching capacity of a combine harvester to area of crop*

As the size of a combine harvester increases, the time required for harvesting a given area is decreased. Investment in a bigger machine can be off-set by reduced labour charges, lower crop losses and better possibilities of exploiting good weather conditions. Simulation of combine operation in the weather conditions during cereal harvest showed the areas at which large and expensive combines were more economical than smaller but cheaper ones, and also the level of seed loss which was tolerable in order to minimize harvesting costs.

The model indicates that with a large combine harvester, of cutting width 5 m, the minimum annual system cost per hectare of harvesting cereals in the north of England is reached at approximately 160 ha and the cost remains approximately constant up to 240 ha. As the area to be harvested is increased beyond this limit, the harvesting cost per hectare begins to rise steeply due to grain losses by shedding during a harvest period which is too prolonged.

(iv) *Disposal of farm wastes*

Applying the ideas of economies of scale to livestock production leads to heavy concentrations of animals in relatively small areas. While such an organization has advantages in management, feeding and marketing, it also produces large quantities of waste material of highly polluting character. Biological treatment of the waste appears to be both difficult and expensive. If the waste is returned to the land for disposal, there is a limit to the quantity which can be spread both for hydrological reasons and to maintain the balance of nutrients in the soil (O'Callaghan, Dodd & Pollock 1973).

Simulation of climatic, cropping and livestock production systems gives the following loadings for a balanced system based on a pig unit in Durham (O'Callaghan, Pollock & Dodd 1971):

	max. permissible loading rate dictated by chemical constraints		no. of years in 15 year period where rate is fixed by	
plane of nutrition	gal acre^{-1} year^{-1}	l ha^{-1} year^{-1}	chemical loading	hydraulic loading
high	9000	100000	13	2
low	22300	250000	3	12

(*c*) *Modification of farm structure*

One result of the mismatch between the capacity of the tractors and farm machinery which are available and the average size of holding on which they are used is a search for economies of scale in the use of tractors and machinery. Already there has been consolidation of smaller farms to get a direct increase in the size of holdings. There has also been considerable modification of size of enterprise within existing holdings through specialization in production. Improvements in scale have also been brought about by contracting services and machinery syndicates.

Projecting forward the trend for tractors and machines to grow in power and capacity, it seems modification of farm structure will need to continue.

4. Innovation

The principal challenge in the use of power in agriculture is the one of scale. Can we provide equipment for the Western European family farm which will make it competitive in costs of production with the larger units that in size are more representative of North America than of Europe? It is worth recalling the minimum sizes which have been proposed as viable farming units within E.E.C.:

dairying	40 to 60 cows	(16 to 32.5 ha)
beef fattening	150 to 250 cattle	(50 to 100 ha)
cereals		(80 to 120 ha)

(*a*) *Automation*

We need to look very closely at the tractor as the main power unit on the farm and decide if we want the present development to continue. An analysis of the power and labour requirements on family farms of 20 ha shows that the power demands could be met with a 20 kW tractor, but that there is a need to reduce the peaks of labour demand and supervision. A small tractor must be able to compensate for its reduced rate of working by acquiring a degree of automation.

The work load of a tractor can be broadly divided into four categories of work:

(i) High draught operations such as ploughing and cultivating which are likely to become of less importance in the future.

(ii) A sequence of repetitive operations in which the tractor travels over the same ground with different implements as in seed bed preparation and planting or mowing followed by tedding and baling.

(iii) Transport mainly within the farm where the same route may be followed by the tractor on several occasions as in conveying silage from fields to clamp or in feeding livestock.

(iv) A stationary power unit for driving a pump, blower or mill.

In hay-making it is acceptable for the farmer to steer the tractor during mowing, whereas it should lay a guidance system for steering itself for tedding and baling. It would also be useful if, when a tractor had been started to pump slurry, it could turn itself off when the job was finished.

An area of research and development in tractors which is of interest both in Western Europe and in developing countries is to assess the possibilities for a tractor of about 20 kW which would be capable of a degree of automatic operation. Such a development could also be regarded as an alternative to the difficult problem of improving the ergonomics of tractors which appears to be confined to the larger models and which drivers will be expected to operate for long periods in order to make them economic.

Automatic feeding and data recording systems need not be very dependent on scale. However, the savings in labour and improvements in management which they would bring to family farms should help to make them competitive with larger units.

Disposal of manures from livestock units is likely to force us to maintain a balance between the size of unit and the area of land to which the manure can be returned. As long as the module is economic in the use of labour, the possibilities for economies of scale are limited to a much greater extent in production than in the marketing of the produce. A high level of management in production depends very much on the acquisition of data about the enterprise and on taking decisions in the light of the data. As the cost of data handling systems is likely to fall there is no need for such facilities to be restricted to 'factory' type units.

(*b*) *Cultivation*

The operation in farming which requires the greatest amount of mechanical energy is cultivation of the soil and preparation of a seed-bed. The need for weed control by cultivation has largely been met by the wide use of chemicals. Our understanding of the mechanism of root development in the soil has improved to the point where it should be possible to revise our ideas about cultivation and plan for a reduction in the amount of energy which should be applied by machinery.

The seed-bed requirements for a plant can be divided into two phases: (*a*) a soil environment for germination of seeds; and (*b*) a soil environment for growth of plant roots. Mechanical energy, in many cases, is required only to prepare a narrow shallow strip of soil in which the seed is placed to germinate. When the plant is growing, it supplies the energy for root growth as long as minimum conditions for root development exist in the soil. In too many cases, at present, the whole mass of top-soil is brought to the germination condition.

(*c*) *Microbial processing*

While the primary conversion of solar energy to food is almost certain to remain through the medium of plants, further processing through animals is likely to be challenged at least in part by microbial processing, which is more suitable for organization on an industrial scale than is either pig or beef production. While agriculture has been trying to extrapolate the broiler experience to the larger animals, the fermentation industries have seen the possibilities in the microbial range where the growth time to maturity is hours instead of years.

Whereas agriculture for most of this century has been a principal benefactor from research in applied biology, by the end of the century it could find itself in competition with industries based on applied microbiology in the same way that some other industries have felt competition from those based on applied chemistry. The efficiency of energy conversion, measured as the yield of cellular material per unit of substrate, is higher with micro-organisms than with ruminant animals. There is plenty of evidence of innovation in devising methods for giving a meat-like texture to vegetable based materials.

5. Conclusions

Energy input to agriculture is dominated by the magnitude of the solar radiation component, but tractors and machinery can influence the efficiency with which we utilize solar radiation by improving the timeliness of planting and harvesting. The main trend in development is for tractors and machines to become larger in size and more powerful: a development which is likely to require modifications in the use and management of machines and in the structure of farms. There is a bias in the design and development of tractors and agricultural machinery towards the large farms which dominate the market for new machines in North America and Europe. However, there are limits to the economies of scale that are possible in the use of farm machines because of the effects of timeliness in the use of machines at planting and harvesting and the restrictions of the low speeds of travel which are used.

Many machines are too big for the majority of West European farms, but it will require considerable innovation to re-direct our experience towards developing smaller and less powerful tractors and machinery. A tractor of low power with a degree of automatic operation is more likely to meet the needs of the majority of farms than a powerful one with good

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ergonomics designed for manual operation over long periods. Techniques of seed-bed preparation which are less demanding in mechanical energy seem probable; they would ease the draught specification in tractor design.

Livestock units based on adequate land to recycle manure appear the most likely way of avoiding pollution by animal wastes. There is no scale problem in providing such units with automatic feeding and data handling facilities.

Simulation models of agricultural processes are likely both to augment, and, to some extent, to replace field experimentation.

REFERENCES (J. R. O'Callaghan)

O'Callaghan, J. R., Dodd, V. A. & Pollock, K. A. 1973 *J. agric. Engng Res.* **18**, 1–12.
O'Callaghan, J. R. & McCoy, J. G. 1965 *J. agric. Engng Res* **10**, 23–35.
O'Callaghan, J. R., Pollock, K. A. & Dodd, V. A. 1971 *J. agric. Engng Res.* **16**, 280–300.

Discussion

D. P. EVANS (*A.D.A.S., Wrest Park, Silsoe, Bedford*). Professor O'Callaghan has presented us with a number of interesting thoughts. I am intrigued by his reference to the utilization of solar energy in relation to crop production, and he did very briefly refer to solar energy in relation to forage conservation. Fossil fuels are going to become more expensive and in the very long term are expendable, and I must say that the practice of utilizing solar energy to make hay and silage is much more commendable. Agricultural engineers have a very important part to play in improving the application of solar energy to conservation, and I am sure future generations will appreciate their efforts.

When he went on to discuss innovations, he only mentioned four. This may be true as far as crop production is concerned, but engineering is concerned with all aspects of agriculture and two other fundamental innovations come to my mind, namely the vacuum-operated milking machine and the buck-rake, and I am sure there are quite a few more.

However, I must agree that modification has had a greater impact, and since industrial mechanization has forged so far ahead we should always be surveying industrial methods and modifying those that appear suitable to agricultural applications.

Unfortunately as far as the tractor is concerned, the main modification appears to be an increase in size. I deprecate this where the aim is to apply the power by tractive means, and in this I appear to be supported by Professor Preuschen and Mr Fox.

Timeliness is all important, but I would like to suggest that in these modern times it can be achieved by the judicious combination of chemical and mechanical methods. The need for deep overall cultivation must be continually questioned and every avenue that will allow more work by other than tractive effort must be explored. Finally may I make a plea for more attention to precision in the application of chemicals and fertilizer. Blanket applications of materials that may be toxic to humans and wild life must be avoided. Every effort to investigate the correct placement of chemicals in the optimum quantities and the development of machines that will allow their safe and accurate placement must be given a high priority.

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