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A Model of an Indian Village: A Study of Alternative Sources of Energy for Irrigation

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Summary. This study analyses the feasibility of various sources of energy for irrigation on the northeast Indian plains. In this region there is a large potential for further use of groundwater, and this paper examines the trade-off between the benefits to agriculture of irrigation, and the costs of the energy and equipment required for pumping.

A linear programming model has been developed to predict the effects on agricultural production of several conventional and non-conventional technologies. Only small size pumps suitable for use by individual farmers or small cooperatives are considered.

The results show diesel-fuelled pumpsets to have the largest net benefits. The general uncompetitiveness of the other technologies is due to the low energy requirements of irrigation in this area

1 INTRODUCTION

The role of energy in the development of the rural areas of developing countries has received much attention in recent years. That mechanical equipment and engines of some form are required to increase agricultural production is generally accepted, although there are widely differing views on the most suitable sources of energy for this technology Particularly many 'renewable' energy technologies have been put forward as the solution to the problems of expensive petroleum fuels

Unfortunately it is often the case that such renewable technologies are advocated with little basis in either technical or economic fact. In this paper a linear programming model of a village economy in northeastern India is formulated. The model is then used to assess the economic impacts of low-lift pumpsets fuelled by several conventional and non-conventional sources of energy

The paper is organized in five parts.

(i) a brief description of the farming systems of the northeast Indian plains, and census data for the village used as a case study;
(ii) an outline of the model,
(iii) a discussion of the most feasible methods of energizing low-lift irrigation
(iv) a discussion of the findings of the modelling exercise and some cost benefit analysis
(v) a summary of the policy implications of the above analysis.

2. SOME CHARACTERISTICS OF AGRICULTURE IN NORTHEASTERN INDIA

The region considered in this study is that of the plains of northeastern India, and particularly the state of Bihar. The northern plain contains the Ganges Jumuna Brahmaputra river system and stretches across the Indian states of Uttar Pradesh, Bihar and West Bengal, to Bangladesh. Generally, the land consists of deep alluvial deposits and is agriculturally rich. Of the order of 30% of the entire population of the Indian subcontinent live on these plains.

North Bihar lies in the centre of this region, just south of the Nepalese border, the north of the Ganges River The population density is approximately 1250 persons per square mile, of which only 10% live in urban areas. Of agricultural households 30% own no land and are

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dependent on seasonal employment for income. An additional 24% of households operates less than one hectare of land (Singh, 1978).

The State of Bihar is considered one of the most backward in India, and agricultural production is low. The census data used in the model are based on data from Pulkahi,[1] a village located close to the town of Dharbanga, and averages for the State. Pulkahi was chosen as it is one of the poorer villages in the region. Resources are tightly constrained and there is no investment in modern equipment. Thus, Pulkahi provides a good case study for the potential development of traditional agriculture into modern mechanized agriculture. Pulkahi contains some anomalies, however, and these are adjusted with data averaged over the State. In this way a 'typical poor village' in North Bihar is constructed.

Table 1a shows this distribution of land ownership for Bihar, India and Bangladesh. Also shown is the distribution of land in Pulkahi. Immediately apparent is the severe shortage of land, and the inequality in ownership. Table 1b shows the number of landless households as a percentage of total households. An increasing fraction of households have become landless due to the rate of population increase (amongst other reasons). The fraction of landless labourers of the total agricultural workers increased from 25% in 1951 to 47% in 1971 (ILO, 1977).

Table 1. *Distribution of land ownership in Pulkahi, Bihar*

(a) *Landholding pattern*

	Percentage of households			
ha	India* (1976)	Bihar* (1976)	Bangladesh† (1968)	Pulkahi (1981)
0–1	55	73	57	72
1–2	18	12	26	12
2–4	25	15	13	5
+4			4	11

*Source: Kalkra (1981).
†Source: Tyers (1978).

(b) *Landless as a percentage of total households*

Kosi* (1971)	Bangladesh† (1977)	Pulkahi (1981)
30	38	57

*Source: Singh (1978).
†Source: Tyers (1978).

In this study the population is categorized by land ownership as this is the main indicator of economic status. The groupings used in the model are: landless, small farmers owning 0.01–2.00 ha and large farmers owning 2.01 ha and above.

A large percentage of the land of Pulkahi is sharecropped. The exact nature of land sharecropping is dependent upon complex social relationships, and many families have sharecropped for a particular larger landowner for generations. Although the Bihar Land Reform Act of 1950 was concerned with the abolition of *Zamindari* (larger landed proprietors) and the transfer of ownership rights to the cultivators of the land, there has been little change. Even the later Bihar Land Reforms Act of 1961 left 'a series of loopholes (which) virtually nullified the redistributive efforts presumably intended by the legislators' (ILO, 1977, p. 108).

The sharecroppers, or *Bataidar*, are usually responsible for financing all the inputs to the crops. Agricultural production is then divided equally between the sharecropper and the landowner. The Gini coefficient for Pulkahi for land owned over the entire population is 0.3. A similar figure across landowning households is 0.7.[2]

There are two distinct categories of land in North Bihar. One category is known as *Champ* land. This land is found in old river beds that are now dry. As it is low-lying it is often flooded for up to half the year and crops that cannot tolerate water-logged soil cannot be grown. Thus, it is normally only single cropped. The second category, known as *Bharna* and *Bhitha* land (the local names indicate a more subtle breakdown) is of better quality. It is multiple cropped and all crops can be grown.

Table 2 summarizes the data used as a basis for the model. Small nuclear families predominate in landless households. Women only work (in agriculture) in the families of landless labourers and marginal farmers, reflecting the poor economic status of these groups.

The annual rainfall for North Bihar is of the order of 1600 mm. Table 3 shows the monthly breakdown of precipitation for the Saharsa district in 1981 (where the village of Pulkahi is located) and the average depth to the groundwater table in Pulkahi. The groundwater is very close to the surface, and during the monsoon much of the land is flooded.

There are three distinct seasons in North Bihar:

(i) The *Kharif*, or autumn, including the

Table 2. *A typical poor village in North Bihar, India*

Household type	Number of households	Mean operated land (ha)	Sharecropped as a percentage of operated land	Bullock ownership	Male buffalo ownership	Family size	Male earners	Female earners
Landless	112	0.05	100%	0.05	0.05	4.5	1.3	0.7
Small	72	0.55	45%	0.60	0.11	6.5	1.5	0.1
Large	14	6.85	0%	1.70	0.90	9.0	2.9	0.0

Land type 45% *Champ*, 55% *Bhitha* and *Bharna* for all categories.
Cattle and buffalo population; adult male : adult female ratio, 1 : 1.17.
Based upon the village of Pulkahi and averages for North Bihar.
Small farmers own less than 2.0 ha, large farmers own more than 2.0 ha.

Table 3. *Precipitation in Bihar*

Month	Precipitation* (mm)	Depth to groundwater† (m)
Jan	34	2.00
Feb	30	2.25
Mar	34	2.50
Apr	109	2.75
May	142	3.00
Jun	167	2.50
Jul	613	2.00
Aug	391	1.50
Sep	131	1.00
Oct	9	1.25
Nov	6	1.50
Dec	0	1.75

*Personal communication, M. N. Jha (1981).
†Based upon linear interpolation of figures for May and September personal communication, M. N. Jha (1981)

months of July to October. This is the monsoon season.

(ii) Early *Rabi*, or winter, which covers November to February. During this time the weather is dry and (relatively) cool.

(iii) Late *Rabi*, or summer, is the period March to June which is hot and dry with occasional showers

The existing cropping pattern for Pulkahi is shown in Figure 1. The major crop is rice harvested during the early *Rabi* season. Other important crops are pulse, wheat and oilseeds

3. A VILLAGE LEVEL MODEL

The interactions among the members of a rural village community are complex, and the introduction of new technology can have many effects that are not immediately apparent

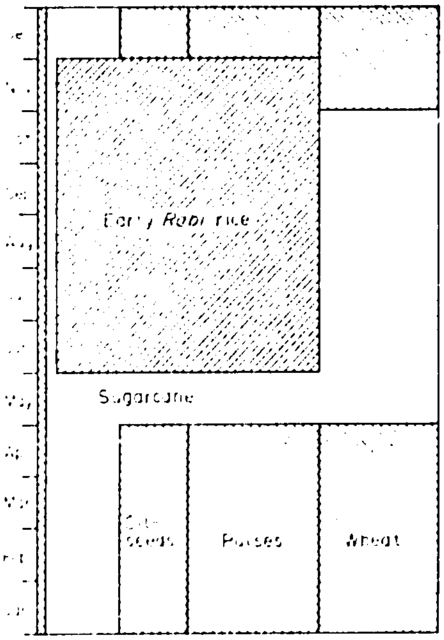

Figure 1

Numerous observations (Mambog, 1979; Islam, 1980, Cecelski, 1979; NCAER, 1978) have been made of the transfer of goods and services within villages in several regions of the world. Briscoe (1979a, p. 12) for example, highlights the complexity of some of the exchanges in the use of crop residues.

> Deep water *aman* paddy . . . produces leaves which are usually used for fodder but, sometimes for fuel; grain which is used for food; husk which is usually used for fuel but sometimes for fodder; *khar*, the upper, tender, straw, which is usually used for fodder but sometimes also used for fuel or compost, and *nara*, the lower, coarse straw which is usually used for fuel but is also used for compost and occasionally for construction and animal fodder

Recently there have also been attempts to identify the interactions between the different activities of village life. One of the first, by Makhijani and Poole (1975), qualitatively compared traditional and modernized villages and the different allocation of resources. Other more quantitative studies include Briscoe (1979a, b), Hart (1980) and Rappaport (1980).

There is a tendency in this type of analysis to follow the approach of Pimentel and Pimentel (1979) of measuring all inputs and outputs in terms of energy and deriving an overall energy efficiency. Although any village system includes an imbedded energy system, the description of all flows in energy units does not capture the value of the goods consumed and produced: one joule of rice is *not* equivalent to one joule of sugarcane. Two measures are therefore required: energy units for items that are direct substitutes in these units (e.g. heat, mechanical work, etc.), and the utility of goods as represented by their prices, for items that are exchanged on established markets (e.g. crops, diesel oil, etc.).

One of the most important systems within the village is that of crop fertilizers (McDowell and Hildebrand, 1980). Animals are an important feature of this system, as although they eat fodder which could be used for green manure, they produce dung and return nutrients to the system. Nitrogen is added to the system by natural fixation and the application of commercial fertilizers. The crop yield is removed from the system (although food eaten by the villagers is returned as faeces, generally directly to the fields) as are residues burnt for cooking. Residues and grasses on fallow fields are also removed as fodder. Dung of less total nutrient value is returned, some of which is burnt for cooking and lost to the system.

The farm system balance of nutrients is very important when the feasibility of biomass-fuelled technology is considered. In many areas, particularly the northeastern Indian plains, biomass is already used for some purpose (e.g. fuel and fertilizer) and may not be freely available for new technology.

In order to study the village system, and to predict how technology will be used, it is useful to construct a mathematical model. This provides a consistent framework for the analysis of interactions between individuals in the village. To quote Edwards (1979): 'The mathematical and computerized model is not merely another language, it is a logical system. . . . It imposes a system of organized reasoning'.

The model used here predicts the general equilibrium state of the village economy from the maximization of profit for farmers, under assumptions of perfectly elastic demand for goods exchanged on established markets. It is also assumed that domestic demand for biomass, and the supply of labour are perfectly inelastic.[3] In more detail the components of the model are:

(a) *Objective function*

The objective function maximizes farmers' income from crops and milk production, less the cost of commercial fertilizer and fuel (when it is used for irrigation). All land hired is assumed to be sharecropped. The sharecropper is responsible for all inputs, but only receives 50% of the crop production.

(b) *Land availability constraint*

As has been noted there are two types of land: multiple cropped, and low-lying single cropped. We assume that only one crop can be present at a given time on the same land. In addition, crops that cannot tolerate water-logging (e.g. wheat, maize) cannot be grown on low-lying *champ* land.

(c) *Crop production functions*

Linear crop production functions are used to relate crop yield to the level of application of fertilizer and irrigation. It is assumed that each feasible crop has a fixed demand for water, fertilizer, animal work and labour, in each time period.

(d) *Fertilizer demand constraint*

Fertilizer requirements are calculated across total land operated for each group. This averaging does not address the costs of distribution of fertilizers. The only nutrient to be considered in this study is nitrogen, and it is assumed that a nitrogen balance exists. A schematic of the nutrient cycle is shown in Figure 2. Nitrogen is lost in the crop yield, and in residue and dung burnt for fuel. Additional nitrogen comes from atmospheric fixation and the application of commercial fertilizers. A given group can also receive residues and dung for fuel from wealthier farmers.

(e) *Animal production constraint*

Animals are included in the model by linear input/output functions relating work, milk and

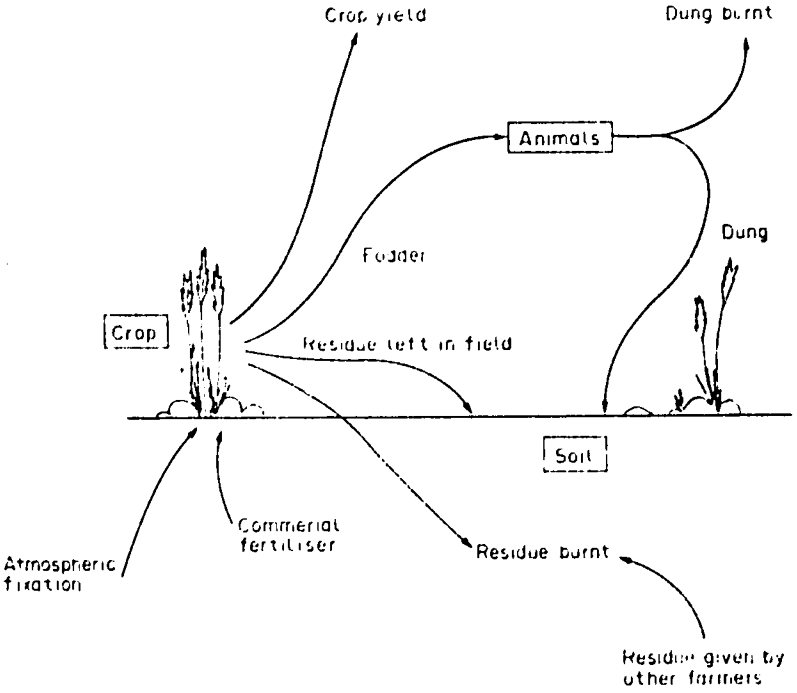

Figure 2.

dung produced to fodder consumed. In addition it is assumed that each category of animal has an upper and lower limit of potential fodder consumption in a given time period. This animal production function is discussed in detail in Hurst and Rogers (1983).

(f) *Domestic fuel demand*

It is assumed that each household has a demand for energy for cooking that must be met. This heat comes from the burning of wood, residues and dung, each of which has a specified efficiency of combustion. Wood production is assumed independent of agriculture and is included in the model by means of a fixed annual availability.

(g) *Labour availability constraint*

The number of hours available for work from each household is set by constraints. In this formulation, a farmer always uses family labour to the limit, before using additional labour from other households. However, the number of hours of work performed by large farmers is quite low, and accordingly the limits on labour availability are adjusted with farm size. It is assumed that a landless labourer can work up to 10 hr/day, that a small farmer can work up to 4 hr/day and that for larger farmers each worker does not work for more than 2 hr/day.

(h) *Technology production functions*

The work available for pumping depends upon the technology and the fuel consumed. The efficiencies of the technologies considered are discussed in the following section. It is assumed that the quantity of water pumped is directly proportional to the amount of work pumped, and an exogenously set depth to the groundwater table. Groundwater draw-down should not be a serious problem due to the low soil retention time, and the large quantities of water flowing through the system. In addition it is assumed that each technology has an operating demand for labour proportional to the shaft work produced.

4. ALTERNATIVE LOW-LIFT PUMPS

Several alternative technologies are available for use with small low-lift pumpsets. However, it is thought that the more feasible alternatives for the next 10 20 years are:

(i) diesel engines fuelled with diesel oil,
(ii) diesel engines fuelled with methane from biogas plants;
(iii) diesel engines fuelled with producer gas from gasifiers;
(iv) animal-powered pumps.

In the time period of 10–20 years, direct solar systems (e.g. photovoltaics, organic rankine engines) will almost certainly not be available at a competitive commercial level.[4] Wind power may be feasible for some areas, but for many others it is simply not windy enough for this to be viable (e.g. the bulk of the Indian subcontinent). Biomass technologies and animal-powered pumps remain the major alternative to fossil fuels.

Biomass can be used in external combustion engines such as the steam and stirling engine or can be converted to alcohol for use in internal combustion engines. However, these technologies are also not considered due either to their very high capital cost or low (technical) efficiencies at small sizes.

At present the major mechanical input to agriculture is from small-scale petroleum-fuelled internal combustion engines. In India these are usually tractors, or stationary diesel engines driving pumpsets or threshers (most of these stationary engines have a capacity of 5–12 HP, although some 3-HP engines are also used).

The efficiencies of such engine pumpsets are the subject of some debate. This is due partially to differing definitions of efficiency. It can be measured in a laboratory, measured in the field, or an efficiency can be estimated for best possible field use. Table 4 shows the efficiency for engine pumpset systems from various sources.

From these figures, the following estimates of the potential field performance of engines are made: 3-HP diesel engine, 20%; 5-HP diesel engine, 28%; direct coupling of engine and pumpset,[5] 95%; pumpset, 65–70%. This gives an overall efficiency of 12% for 3-HP engine-pumpsets.

Table 5 summarizes some characteristics of the technologies included in this study. The technology of anaerobic decomposition, or biogas production, has been the topic of many studies and is often recommended. There are two designs that have been widely adopted in both India and China. These are the KVIC floating-dome plant, and the Janata or Chinese, fixed-dome biogas plant. There is little difference in the technical performance of the two designs, although the fixed-dome plant is completely underground and better insulated from fluctuations in atmospheric temperature. The major difference (and cost) of construction is the mild steel required for the gas collector in the floating dome design.

One non-energy advantage of biogas plants is that the spent sludge contains the same nutrients as the feedstock. Additionally, digested sludge

Table 4. *Petroleum engine-pumpset efficiencies*

Pump efficiency (1)	Transmission efficiency (2)	Pump-transmission efficiency (3)=(1)×(2)	Diesel engine efficiency (4)	Overall efficiency (5)=(3)×(4)	Source
–	–	–	35	–	a
–	–	–	28	–	b
41	85	35	25	9	c
–	–	28	20	6	d
–	–	–	–	20–25	e
–	–	–	–	18	f
–	–	–	–	13–15	g
–	–	66	20	13	h

Sources:
(a) Engine manufacturers (India) 5 HP diesel.
(b) Engine manufacturers (India) 3 HP diesel.
(c) Patel and Gupta (1979) estimated normal performance for 3-HP engine.
(d) Patel and Gupta (1979) measured performance for 3-HP engine.
(e) Jensen (1980) maximum performance.
(f) Jensen (1980) recommended performance.
(g) Jensen (1980) field test.
(h) Figures for (f) broken down assuming a pump-transmission efficiency of 66%.

b

Table 5. *Efficiencies of various technologies*

System	Fuel	Biomass conversion efficiency (%)	Engine efficiency (%)	Pump efficiency (%)	Probable overall efficiency (%)
Conventional diesel engine	Diesel oil	–	28–20	60	15–12
Biogas plant	Dung	40	28–20	60	6–4.5
Gasifier	Residues	30	28–20	60	4.5–3
	Wood	40	28–20	60	7.5–4.5
Animal-powered systems	Residue	7		50	3.5

These figures are discussed in more detail in Hurst (1983).

is reported to have a higher percentage of ammoniated nitrogen which is more easily absorbed by plants (Bhatia, 1979).

Many types of material can be used to fuel biogas plants including agricultural residues, human and animal faeces and aquatic weeds. Plant matter resistant to digestion requires pretreatment with enzymes or acids (Santerre and Smith, 1982). This technology is still at an experimental stage in most cases, and in India cattle dung will remain the major feed in the near term.

Gasification is another technology which appears to be technically very attractive.[6] Of all the 'appropriate' technologies, it is probably one of the least understood in terms of performance and costs. This is surprising since gasification is by no means a new technology. It is old and well-tried, and during World War II some 3.5 million engines were powered by gasified wood, charcoal and coal (National Academy of Sciences, 1982).

The efficiency of a small gasifier is of the order of 60%. For small systems, however, it is advisable to use charcoal as a fuel. Other fuels (wood, residues) produce tars that are harmful to engines and that can only be removed by expensive filters.[7] Charcoal adds complication of the system and reduces the overall efficiency by approximately 50%. The overall efficiency for a charcoal manufacturer gasifier diesel engine is approximately 7.5%.

The final category of pumps considered here are animal-powered pumps. For centuries, long before Otto conceived of the internal combustion engine, irrigation has been done by animals. In the Indian subcontinent it is usually bullocks or buffalo that are used, and these can produce of the order of 250 750 W of work depending upon their size and nutrition. Perhaps the most common animal powered pumps are the Persian wheel and the chain and washer pump. For both these pumps, the gearing involved in transferring a horizontal rotary motion into a vertical one is very simple two intermeshing wheels at right angles. However both require brick-lined open wells (generally 4–5 ft in diameter) down to the groundwater table (these are much more expensive than tubewells).

An interesting new idea by G. S. Nijjar[8] is the Bullock Powered Tubewell (Hurst and Rogers, forthcoming). This mechanism relies, like the traditional pumps, on a bullock walking in a circle. But here, the rotary motion powers a centrifugal pump attached to a tubewell. Tubewells and centrifugal pumps are widely used at present with diesel pumpsets. Their advantages are that centrifugal pumps are mass-produced and cheap, and tubewells are much easier and cheaper to install than open wells. Centrifugal pumps only operate at a speed of approximately 1000 rpm or more. Bullocks walk at about 1.25 m/sec or approximately 3 rpm for an 8-m diameter circle. Therefore a gearing mechanism is required with a gearing ratio of about 350. Nijjar's present equipment is in the experimental design stage and measurements have not been made. However, 50% efficiency (not including the bullock) is consistent with the reported efficiencies of traditional systems.[9] In addition, animal metabolism has an efficiency of approximately 7% for the conversion of fodder to work (Hurst and Rogers, 1983). This gives an overall efficiency for animal-powered pumps of 3.5%.

5. IMPACTS OF IRRIGATION TECHNOLOGY

The model described in Section 3 was solved using the SESAME Linear Programming package on the IBM 360-168 at the Massachusetts Institute of Technology, USA. Various levels of model complexity were assessed before the final model was chosen. The final model used to estimate the impacts of technology on the village system comprised:

(i) three household categories: landless, small farmers and large farmers;

(ii) four categories of animals: male buffaloes, bullocks and cows;

(iii) 16 different possible crops; the complete list of crops is shown in Table 6;

(iv) three time periods: December to March, April to July, August to November. While these model seasons do not coincide with the traditional seasons of Early and Late *Rabi*, and *Kharif*, they are more appropriate for capturing the physical interactions of crops on the land. The crop season for each crop is illustrated in Figure 3.

This model has 299 rows, 345 columns and a matrix density of approximately 0.016.

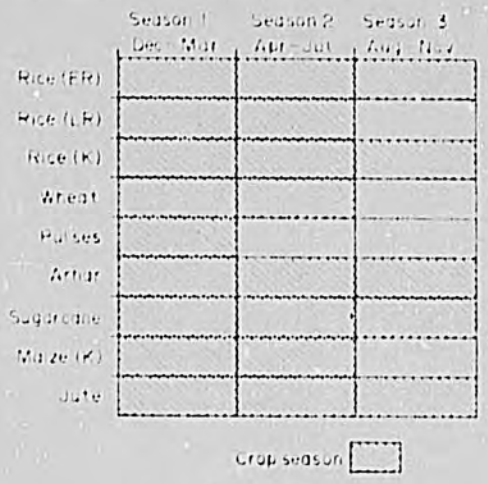

Figure 3.

Table 6. *Crops used in the village model*

Crop	Variety		Fertilizer			
	Traditional	High yielding	Minimum	Maximum	Irrigation	Production (Rs/ha)
Early *Rabi* Paddy	X		X			464
Early *Rabi* Paddy	X			X	X	640
Early *Rabi* Paddy		X		X	X	1426
Kharif Paddy	X					464
Kharif Paddy		X		X	X	1426
Late *Rabi* Paddy	X					632
Late *Rabi* Paddy		X	X		X	1010
Late *Rabi* Paddy		X		X	X	1447
Wheat	X		X			772
Wheat		X		X	X	1321
Maize		X	X			776
Pulses	X		X			590
Arhar	X		X			640
Sugarcane	X		X			1944
Sugarcane	X		X		X	2160
Jute	X		X			810

The cropping pattern obtained from the model is shown in Figure 4.[19] The major crop of this combination is traditional Early *Rabi* Paddy which covers two thirds of the land area. Some pulse is multi cropped with the paddy, and some wheat and *arhar* (a local variety of pulse) are also grown.

Figure 4 also shows the actual cropping pattern observed in Palkahi for 1980. As can be seen there are strong similarities between the model solution and the actual activities of the farmers of Palkahi.

The model was run under different scenarios of technological endowment. The various technologies considered were summarized in Table 5. The efficiencies chosen for each technology are somewhat pessimistic, however they are more realistic for the near term. For each technology, two scenarios were considered: ownership of irrigation technology by large farmers alone, and ownership of irrigation technology by both small and large farmers. It was assumed that large and small farmers (if they own the technology) each had a capacity of up to 20 and 10 kW of work respectively.

The model solutions for all technologies except the animal-powered scenarios were all either remarkably similar or identical. Figure 5

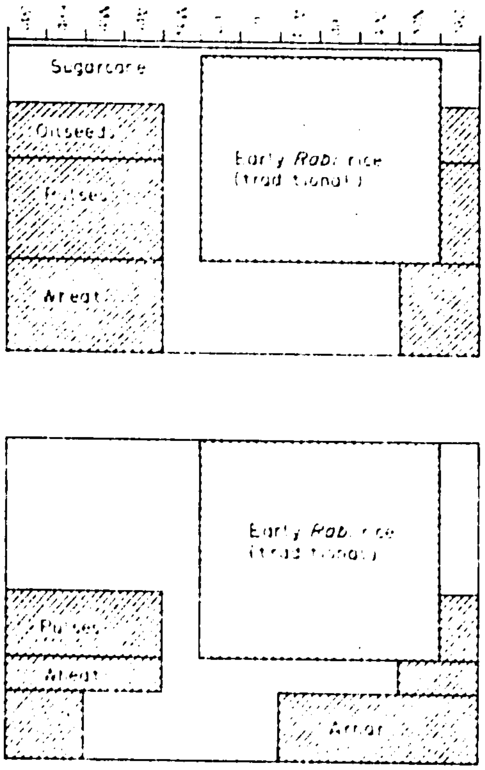

Figure 4.

shows the aggregate village optimal cropping pattern when large farmers own irrigation technology. The typical village optimal cropping pattern when both large and small farmers own pumpsets (again excluding animal-powered systems) is shown in Figure 6. The major impact of irrigation is the adoption of irrigated, fertilized high yielding varieties of rice in both the early and late *Rabi* seasons. Wheat is no longer grown, and although more pulse is grown, less *arhar* (also a variety of pulse) is planted. The cropping pattern of land sharecropped by landless households is unaffected by the technological endowments of other farmers.

Unlike the other methods of pumping water discussed (i.e. using internal combustion engines) there is an important technical constraint to the use of animals for pumping: there is a maximum capacity of work that can be performed for a given number of animals (the size of the herd is kept constant) regardless of the number of pumps that are installed.

A bullock or buffalo can only work in the sun for about 6 hr, and it cannot produce more than an average of approximately 500 W. With a pumping mechanism of 50% efficiency, and an average depth to the groundwater of 1.0 m (after the monsoon), one animal can pump 16,200 m^3 of water in one month.

This implies that large farmers owning an

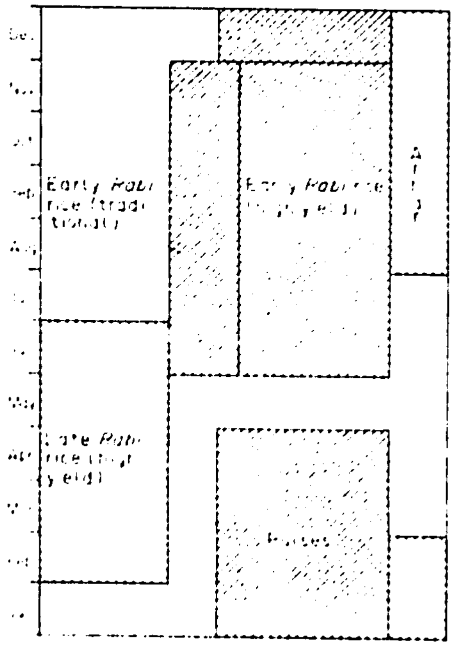

Figure 5.

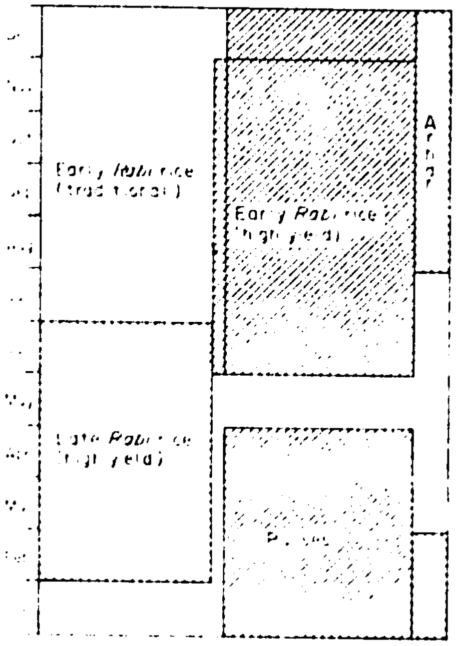

Figure 6.

average of 2.6 draught animals could pump 42,100 m^3 of water, sufficient to irrigate up to 4.2 ha of Early *Rabi* rice. Small farmers with an average of 0.7 draught animals could produce 11,500 m^3, or sufficient irrigation for 1.15 ha of Early *Rabi* paddy (this assumes irrigations must be applied within one month).

In the Late *Rabi* season, the groundwater is deeper (at an average depth of 2.5 m) and only 4600 m^3 could be pumped by a small farmer; a large farmer could pump 16,800 m^3. This quantity of water can irrigate 0.23 ha and 0.84 ha of Late *Rabi* paddy respectively.

From the model solutions, the optimum level of irrigation (without capacity constraints) is 0.16 ha of Early *Rabi* rice and 0.24 ha of Late *Rabi* rice for a small farmer, and 3.8 ha of Early *Rabi* rice and 3.1 ha of Late *Rabi* rice for a large farmer. Therefore, although animal-powered pumps can meet fully the irrigation demands of small farmers, if they are used by large farmers then only 0.84 ha of paddy (per farmer) can be irrigated in the summer, and 2.26 ha (per farmer) of traditional Late *Rabi* paddy must be grown instead of the higher yielding variety. This results in a loss of income from the unconstrained optimum of 1860 Rs/household (the difference in income between irrigated, fertilized, high yielding Late *Rabi* paddy and traditional unirrigated, unfertilized Late *Rabi* paddy is 820 Rs/ha).

Thus far the capital costs of the various irrigation devices have not been included, and it is not surprising that the model predicts extensive irrigation. The investment in capital was not included in the model as it was thought that the factors determining investment were too complex to be included endogenously. Instead, the net economic effect of each technology is calculated through cost benefit analysis with the benefits from agriculture of irrigation measured from the model prediction relative to the solution with no mechanical equipment. In this analysis, labour is priced at 3.0 Rs/day. The major change in the use of labour comes from the change in cropping pattern rather than for operating the pumps.

As mentioned previously, the engine capacity constraints were set at 20 kW for large farmers and 10 kW for small farmers. For a maximum pumping rate of 8 hr/day, this is equivalent to 69,100 and 34,600 MJ for each season. The model solutions show, however, that the maximum utilization of each technology is only 14,000 MJ/season for large farmers and 5250 MJ/season for small farmers. This work demand could be met by an installed capacity of: 15 kW (20 HP) for large farmers, and 6 kW (8 HP) for small farmers, for an average pumping time of 2 hr/day over the 120-day season. This capacity would obviously require a large degree of social cooperation within farm categories. For example, assuming that the small farmers owned three 3-HP engines and the large farmers owned four 5-HP engines, there would only be one engine for every four large farmers and one for every 24 small farmers (although all farmers within each group would use them). It is highly unlikely that such a state could exist in a traditional Indian village and it is more likely to assume that for complete irrigation (or more exactly, the level predicted by the profit maximizing state of the village economy) each large farmer would own their own 3-HP engine pumpset (or possibly share one with one other farmer), and that every four small farmers would have access to one 3-HP engine pumpset. This gives an installed capacity of 42 HP (31.5 kW) for large farmers and 54 HP (40.5 kW) for small farmers.

The capital costs of owning and operating a diesel engine pumpset are shown in Table 7. Table 8 shows similar costs for biogas plants and gasifiers. With these biomass technologies it is still necessary to purchase a diesel engine, pumpset and tubewell in addition to the biomass conversion device.

The capital costs associated with animal powered pumps are shown in Table 9. Two different mechanisms are considered: the traditional Persian wheel and the bullock-powered tubewell. These technologies are discussed in Section 4. The annual maintenance costs associated with animal-powered pumps are also shown in Table 9. Immediately apparent is the large cost of a dug well required with Persian wheels.

Table 10 summarizes the net annual effects of each technology. Capital costs are annualized at an interest rate of 15% over a period of 10 years, diesel oil is priced at 4.0 Rs/l, and commercial fertilizer is priced at 5.4 Rs/kgN. For the biomass technologies, it is assumed that 10% diesel oil is used as fuel. This is required to ensure that there is correct ignition of the biogas or producer gas.[11] In these calculations it is assumed that large farmers either own individual technologies or share with one other farmer, and that small farmers have cooperative ownership of one system between four households.

It is unlikely that small farmers will adopt any technology as they are all uneconomic even if four small farmers have cooperative ownership of one system. During sensitivity analysis of the model solutions it was observed that land sharecropped by small farmers is the most sensitive

Table 7. *Costs of owning and operating a diesel engine pumpset (not including fuel)*

Component	Capital cost (Rs)	Other annual costs: Replacement cost (Rs/yr)	Other annual costs: Lubrication costs (Rs/h of running time)	Life (yr)
Diesel engine (3 HP)	3770*	380†	0.4‡	10
Pumpset	500§	0	0	10
Bamboo tubewell	1000‖	0	0	5

*Source: Rogers (1981).

†Estimated at 10% of capital costs.

‡Based on an oil consumption of 0.1 l/hr of running time.

§Based on 430 Rs for a 2-HP pumpset quoted by Bhatia (1980).

‖Source: Bhatia (1979).

Table 8. *Costs of owning and operating biomass-fuelled technology*

Biomass technology	Capital cost (Rs)	Replacement cost (Rs/yr)	Life (yr)
Biogas plants (5.4 m^3/day)			10
(a) floating dome	5780*	100	
(b) fixed dome	3960†	100	
Gasifiers			10
(a) residue fuel	3800‡	100	
(b) wood fuel	3800‡	100	

*Based upon linear interpolation on 1977 prices of 2330 Rs for 2 m^3 capacity and 5020 Rs for 8 m^3 capacity (Bhatia, 1979) and 50% inflationary increase.

†Based upon 1977 prices of 2640 Rs (Bhatia, 1979) and a 50% inflationary increase.

‡Based upon 770 Rs/HP of shaft power for the gasifier (Rogers, 1981), 500 Rs filters and 1000 Rs for charcoal production.

Table 9. *Costs of owning and operating animal-powered pumps*

Mechanism	Capital costs (Rs): Well	Capital costs (Rs): Pump	Capital costs (Rs): Total	Maintenance costs (Rs/yr)	Life (yr)
Bullock-powered tubewell	1000	3500	4500	170†	10
Persian wheel	5000*	2500	7500	150‡	10

*Open well.

†5% of capital costs.

‡5% of pump capital cost plus 25 Rs/yr for the open well.

Table 10. *Summary of the economic effects of technology*

	Case number		Net benefits; 1 system per household (Rs/yr)	Net benefits; 1 system for 4 households (Rs/yr)	Net benefits; 1 system for 2 households (Rs/yr)	Increase in the price of oil required for break-even; 1 system for 2 households† (%)
	(i)	(ii)	(i)	(ii)		
Diesel-engines	1	2	700	-240	1470	0
Biogas plants (floating dome)	3	4	-250*	-540*	1150*	50
Biogas plants (fixed dome)	3a	4a	110*	-450*	1330*	22
Gasifiers (residue-fuelled)	5	6	110	-440	1330	25
Gasifiers (wood-fuelled)	7	8	50	-420	1250	34
Persian wheels	9	10	-850	-230	-35	..
Bullock-powered tubewell	11	12	-270	-90	270	–

(i) Effects on large farmers, ownership by large farmers only.
(ii) Effects on small farmers, ownership by small and large farmers.

*Includes credit for fertilizer value of spent sludge.
†This is also equivalent to the increase in the depth to the groundwater table required to make each technology competitive with diesel-fuelled engines.

to changes in the model parameters, and that if (i) engine efficiencies are reduced, or (ii) fertilizer prices are increased, then the small farmers revert from irrigated crops to traditional crops on their sharecropped *champ* land. This is because farmers receive only 50% of the production from share cropped land, the remainder going to the landowner. This added sensitivity makes it also unlikely that larger cooperatives would form. In this analysis it is assumed that small farmers are responsible for financing their own pumpsets, although in the case of sharecropped land the landowner may in fact make a contribution towards capital costs. In addition there are some costs of cooperation not included in these calculations.

Of all the technologies, only diesel-fuelled engines have a significant positive net benefit if each large farmer owns an engine. However, if there is a joint ownership between two farmers, all systems become profitable except the Persian wheel. The diesel-fuelled scenario remains optimal. Table 10 also shows the increase in the price of diesel oil (or an increase in the depth to the groundwater) required to make each system profitable (the base price of oil is 4 Rs/sec). It should be emphasized that as the Persian wheel and biogas systems cannot be moved,[12] it may not be feasible to use them for irrigation if the fields are fragmented and separated by large distances (which will be the case for many farmers). If there is an increase in the price of oil by approximately 25–30% then gasifiers become profitable.

A major reason for the general uncompetitiveness of biomass-fuelled technologies is the low head through which irrigation water must be pumped. Effectively, biomass systems substitute an annual cost for diesel oil with an initial capital cost for equipment.[13] In all cases, a diesel engine, pumpset and tubewell must be installed. In the village model (and large areas of the northeastern Indian plains) the consumption of diesel required is low, and is not sufficient to justify the investment required by biogas plants or gasifiers unless there is joint ownership.

Animal-powered pumps are the least competitive of all the irrigation systems for large farmers. This is due to the work capacity restriction from animals and the loss of income from the high-yielding irrigated summer rice crop. This capacity constraint is not a problem for small farmers as they own sufficient animals to fully irrigate their land. However, the Persian wheel devices are as expensive as the diesel and biomass technologies. The bullock-powered tubewell is much cheaper, and is the most profitable of all irrigation systems for small farmers.

Unfortunately, even ownership of this technology would have a net negative effect of 90 Rs/yr/household.

The technology of the Persian wheel has existed for many centuries and is known in India. However, no Persian wheels are used in Pulkahi, confirming the above result. Persian wheels are used in some places in the north-eastern Indian plains and this may be due to non-homogenous ownership of resources within farm groups.

So far discussion has been focused on the financial analysis from the farmers' point of view. For the position of society, however, the most cost-effective at market prices may not be the most desirable.

Two of the most important social objectives for India are creation of rural employment, and reduction of foreign imported equipment and material. For these reasons, the cost of rural labour can be shadow priced as zero,[14] and foreign exchange at 125% its market price. The social costs of each technology are shown in Table 11.

Table 12 shows the net social benefits to the village from different technological endowments. These figures are calculated by shadow pricing diesel oil at 6 Rs/sec (a 50% increase), and commercial fertilizer at 6.75 Rs/kgN (a 25% increase). A social discount rate of 15% is used to annualize capital costs over a time period of 10 years.

Given the desirability of indigenous technology, the biomass technology and the animal-powered systems are much more competitive with the diesel-fuelled engine. This is due predominantly to the large fraction of local labour that is used in constructing these pumpsets. Even with shadow pricing, there is only a minor increase (with the animal-powered systems) or a decrease (with all other technologies) in village welfare if small farmers own pumpsets in addition to large farmers.

Focusing on the engine-powered (both diesel and biomass) scenarios, the most socially optimal scenario of ownership of engines by both small and large farmers (fixed-dome biogas plants; one system for two large farmers, one system for four small farmers) is less than the diesel-fuelled scenario (with one engine per large farmer household).

Considering ownership of pumps by large farmers alone (with one unit per household) then there is little difference between technologies, although fixed-dome biogas plants are the most socially optimal. If it is assumed that

Table 11. *Breakdown of social costs for each technology*

Technology	Capital cost (Rs)	Annual replacement cost (Rs/yr)	Life (yr)
Diesel engine (3 HP)	4150*	420*	10
Pumpset	550*	0	10
Bamboo tubewell	650†	0	5
Biogas plant (floating dome)	4480‡	0	10
Biogas plant (fixed dome)	1980§	0	10
Gasifiers	4000‖	0	10
Persian wheel (including well)	3130¶	0	10
Bullock-powered tubewell mechanism (including pump)	2500**	0	10

Labour shadow priced at zero; foreign exchange premium 25%.
*40% foreign exchange component.
†35% labour.
‡30% labour, 30% foreign exchange component.
§50% labour.
‖Gasifier, 40% foreign exchange component; charcoal producer, 50% labour.
¶Open well, 70% labour; mechanism 35% labour.
**Pump, 40% foreign exchange component; mechanism 35% labour.

Table 12. *Net social benefits of agriculture*

Technology	Case number	Net village social benefits from agriculture (Rs/yr) 1 Unit per household for large farmers		1 Unit for 2 households for large farmers	
Diesel engines	1	113,400	(100)	124,300	(100)
	2	**95,200**	**(84)**	**106,200**	**(85)**
Biogas plants	3	111,900	(99)	129,100	(104)
(floating dome)	**4**	**82,300†**	**(73)**	**99,500†**	**(80)**
Biogas plants	3a	118,900†	(105)	132,600†	(107)
(fixed dome)	**4a**	**98,300†**	**(87)**	**111,500†**	**(90)**
Gasifiers	5	112,300	(99)	128,800	(104)
(residue-fuelled)	6	80,200	(71)	96,700	(78)
Gasifiers	7	111,000	(98)	127,500	(103)
(wood-fuelled)	**8**	**83,700**	**(74)**	**100,200**	**(81)**
Persian wheels	9	114,600	(101)	119,000	(96)
	10	**114,700**	**(101)**	**119,000**	**(96)**
Bullock-powered tubewell	11	114,600	(101)	119,000	(96)
	12	**114,700**	**(101)**	**119,000**	**(96)**

Figures in roman type: ownership by large farmers only; figures in bold type: ownership by small and large farmers.
Base case 94,500 Rs/yr; engine capacity 3 HP.
*Assuming 1 engine for 4 small farmer households.
†Includes credit for fertilizer value of biogas plant sludge.

large farmers share technologies (with one system for two households), the initial capital investment is reduced, and all biomass technologies become better than diesel engines alone. Again the fixed-dome biogas plant is marginally superior to the other systems. However, the benefits of cooperative ownership are much smaller for animal-powered pumps, and these become the least profitable alternative.

In these calculations the minimum possible shadow price for labour has been used. If a subsistence wage of 3 Rs/day/worker were used instead, then the diesel-fuelled engine would be optimal in the case of individual ownership by large farmers, and 98% of the optimal for joint ownership. Although it is possible that a central authority may want to give subsidies for biomass technology, it is probable that the costs of implementing a subsidy programme would outweigh its benefits.

6. CONCLUSIONS AND IMPLICATIONS

The use of irrigation increases agricultural yields and increases rural incomes. However, small farmers (on the northeast Indian plains) do not have sufficient resources to warrant the purchase of any irrigation system, and both they and landless households must rely on increased employment by large farmers (and perhaps the purchase of water) to share in the benefits of new irrigation technology.

At current prices, large farmers (on the northeast Indian plains) should choose diesel engines over biomass technology or animal powered pumps. As has been noted, the problem with biomass technology in this region is that the groundwater is near the surface and the cost of diesel fuel is not sufficiently large to compensate for the capital cost of biomass technology. However, at a 20–25% increase in depth to the groundwater table both residue-fuelled gasifiers, and fixed-dome biogas plants become more profitable than diesel-fuelled pumpsets. This suggests that biomass technology can still play an important role in many other parts of India and Southeast Asia.

The results of this study show that the removal of biomass from the village system is not a serious problem. Although the ratio of crop to biomass for high-yielding paddy is approximately half that of traditional varieties, the well-irrigated and fertilized high-yielding crop produces twice as much rice as traditional paddy. In addition, the increase in crop production, and hence the value of irrigation, is such that commercial fertilizer can be used to compensate for nutrients removed from the system by biomass consuming technology.

From the viewpoint of society (that is Indian society) it may be beneficial to encourage the use of biomass technology and possibly animal-powered pumps due to their favourable effects on the national balance-of-trade. However, the shadow pricing of Section 5 shows that no technology has *major* advantages over any other technology.

It is reasonable to pose the question: if it is economic for large farmers to own diesel engines, why are they not used extensively at the moment? The two main reasons are: risk aversion of farmers in adopting new technology, and farmers' lack of information on the costs and benefits of owning this technology. The latter is perhaps an area where government involvement can have large dividends. Through educational programmes and loans to farmers (at a fair but not necessarily subsidized rate of interest) the use of diesel engines may become much more widespread. It may also be the case that more profitable investments can be made outside agriculture through money lending and trading.

The main alternative to the small decentralized engines that have been the focus of this paper is rural electrification. The issues involved with optimal electrical distribution networks and the pricing of electricity are complex and outside the scope of this study.

However, a major problem with rural electrification is the long lead times (after large capital investment) before demand rises to meet the installed capacity. If in the future the use of diesel engines is to be superseded by rural electrification, these small engines can still play an important role in stimulating and establishing a demand for energy for irrigation.

This study has been directed at the optimal investment in irrigation technology by the members of a highly individualistic society. The cost–benefit calculations of Section 5 show that the welfare of farmers can be increased by cooperation (however, no estimates are made for the costs of cooperation). This is particularly the case in the northeast Indian plains where the groundwater is close to the surface and only a small engine capacity is required for complete irrigation. Although a change in social organization and collective ownership of irrigation technology would certainly be beneficial for all involved (and would have major redistributive effects) it is unlikely that rural Indian society will change in the near future.

The use of a model requires the estimation of many, sometimes uncertain, coefficients. However, a model provides a consistent framework for the comparison of alternative technologies. A model such as outlined in this paper may have an important role in aiding decision-makers involved with rural policy. A simple model allows for sensitivity analysis and gives insights into the interactions of the rural system. In this way, issues for a more detailed socio-economic or technical analysis can be highlighted.

Finally, it should be emphasized that the technical parameters of both the biomass technology and the animal-powered systems are uncertain. Further research and development is required to improve existing designs and to determine more exactly their operating characteristics.

NOTES

1. The data for Pulkahi comes from an on-going research effort by M. N. Jha, P. Rogers and R. Bhatia, sponsored by the Ford Foundation, Delhi. The data was collected by M. N. Jha of the A. N. Sinha Institute, Patna, and I am grateful to him for permission to use this data.

2. A Gini coefficient of 1 is equivalent to perfect equality. A Gini coefficient of 0 is equivalent to the state when all the resources are owned by one individual in the society.

3. These assumptions are very specific and contain many implications regarding farmer behaviour and the rural economy. Whether farmers are profit-maximizing, or show significant risk aversion has been the topic of much debate. As no data is available to estimate farmer risk aversion, simple profit-maximizing is used in this model. These issues are discussed more fully in Hurst (1983).

4. Except for drying purposes where it is used already.

5. In Bihar the groundwater is close to the surface and most pumpsets are directly coupled to the engine.

6. Gasification is no more than incomplete combustion. The reactions are:

$$C + \tfrac{1}{2}O_2 \rightarrow CO$$

$$2C + H_2 + 1\tfrac{1}{2}O_2 \rightarrow CO + CO_2 + H_2$$

Both CO and H_2 are combustible gases.

7. See Hurst and Rogers (1982) for a discussion of small scale gasification.

8. Research Officer, Mentha Research Centre, Richardson Hindustan Ltd., Bilaspur, Himachal Pradesh, India.

9. See, for example, Birch and Rydzewski (1980) for data on pumping rates.

10. An extensive discussion of the model and the various scenarios analysed is given in Hurst (1983).

11. Biogas and producer gas do not self-ignite at the peak temperatures of a typical diesel engine cycle. The injected diesel oil acts in the same way as a spark plug, by producing a flame that ignites the compressed gas.

12. The bullock-powered tubewell can be made portable.

13. In this framework the price of biomass is automatically included by the use of commercial fertilizer necessary to maintain a nutrient balance. The price of energy in the form of biomass is cheaper, however, than an equivalent quantity of diesel oil.

14. Although labour can never have a zero shadow cost -- some search is required to look for a job – it is used here as it is the limiting case for labour subsidy.

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