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MODELING ENERGY AND AGRICULTURE INTERACTIONS: AN APPLICATION TO BANGLADESH

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FOREWORD

Understanding agricultural policy options at national and international levels has been the major objective of the Food and Agriculture Program of IIASA. Our attempt has been to explore policy options in a framework where the behavioral responses of various economic agents in the context of the constraints they face are appropriately accounted for.

The interations of energy and agricultural related issues can be of considerable significance in determining agricultural policies in a number of situations, particularly for many developing countries where energy and agriculture systems in rural areas are highly interdependent.

In this paper Jyoti Parikh and Gerhard Krömer present a model for exploring energy and agricultural interaction and its empirical application to Bangladesh.

Kirit Parikh
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ABSTRACT

A linear programming model is developed to capture energy and agricultural interactions existing in the rural areas of developing countries. Energy used for agriculture includes fertilizers, irrigation and mechanization. Therefore several technological choices of each of the above are considered and so are several crop commodities, several types of livestock and farmers of different income groups. On the demand side, the uses of these for feed, fuel and fertilizer have to be considered which then in addition link up household sector, which is the largest user of non-commercial energy, rural industries sector and agriculture sector. Twelve different energy sources and several conversion technologies such as bio-gas, charcoal kilns, alcohol distilleries etc. are considered.

The model is applicable to low income, biomass scarce developing countries. However, different types of countries would require different approximations and their needs for detailing some aspects or the other may vary. A detailed application is done for Bangladesh for which the situation in 1976-77 is simulated first. This base case itself gives insights into the present behavior of different income groups with regard to choices of fuels and allocation of biomass for various purposes. Since Bangladesh is a very low income country choices of biogas, charcoal kilns and alcohol distilleries have little relevance and also choices of mechanization.

It is shown that due to high needs and prices of fuels, the biomass allocation for fuels takes priority over feed and fertilizers. In fact, the landless burn all and small farmers burn 80% of animal dung rather than use it for fertilizers.

The model also shows that unless carried out by substantial amounts of fertilizers, the small and middle farmers would have fodder and fuel shortages on adopting high yielding varieties (HYV) which minimize straw:grain ratios. Similarly, by 1990, when population increases further, middle farmers also become vulnerable in meeting their feed, fuel, fertilizer requirements. To mitigate these effects, improved stoves and other measures would be necessary to increase biomass use efficiencies considerably.

PREFACE

Rural energy system of the developing countries is largely dependent on agriculture and forest land. Therefore, a model incorporating energy required for agriculture and energy derived from agriculture provides an appropriate framework for analyses of a number of issues ranging from pricing of fuels, fertilizer and feed, introduction of technological changes, such as high yielding varieties, bio-gas, charcoal kilns and alcohol distilleries, the role of animal labor, etc. The present model essentially helps in understanding possible short-term changes that could be introduced in the system and how they would affect different income groups in a rural economy. The treatment of income groups and how different policies and changes affect them in a model for energy and agriculture interactions and their empirical applications to rural Bangladesh are some of the contributions of this study and so is the fact that the decisions are made from farmers' points of view in response to external changes.

ACKNOWLEDGMENT

The model developed here owes much to the support provided by the Centre for World Studies (CWFS). Part of the data gathering was also completed with the support of the CWFS. The author is deeply indebted to Michiel Keyzer and Wouter Tims for initiating this work and for providing sustained moral support, and to H. Asseldonk, H. Stolwijk and W. Kennes for their suggestions and ready help concerning data required for the model. Professor T.N. Srinivasan and J.P. Hrabovszky have critically gone through this manuscript and made valuable suggestions. Jan Morovic has helped analyzing household energy data.

This model, which is a submodel of the much larger exercise carried out at the CWFS, had to be modified to run as an independent model. This part was done with the support of the Control Data Corporation, as were the runs concerning application to Bangladesh. For this purpose, suggestions from Kirit Parikh are gratefully acknowledged.

We thank B. Riley and L. Roggenland for typing drafts of this manuscript.

PART I

RURAL ENERGY SYSTEMS MODEL

Jyoti Parikh

1. INTRODUCTION: BACKGROUND AND PROBLEM STATEMENT

1.1. Background

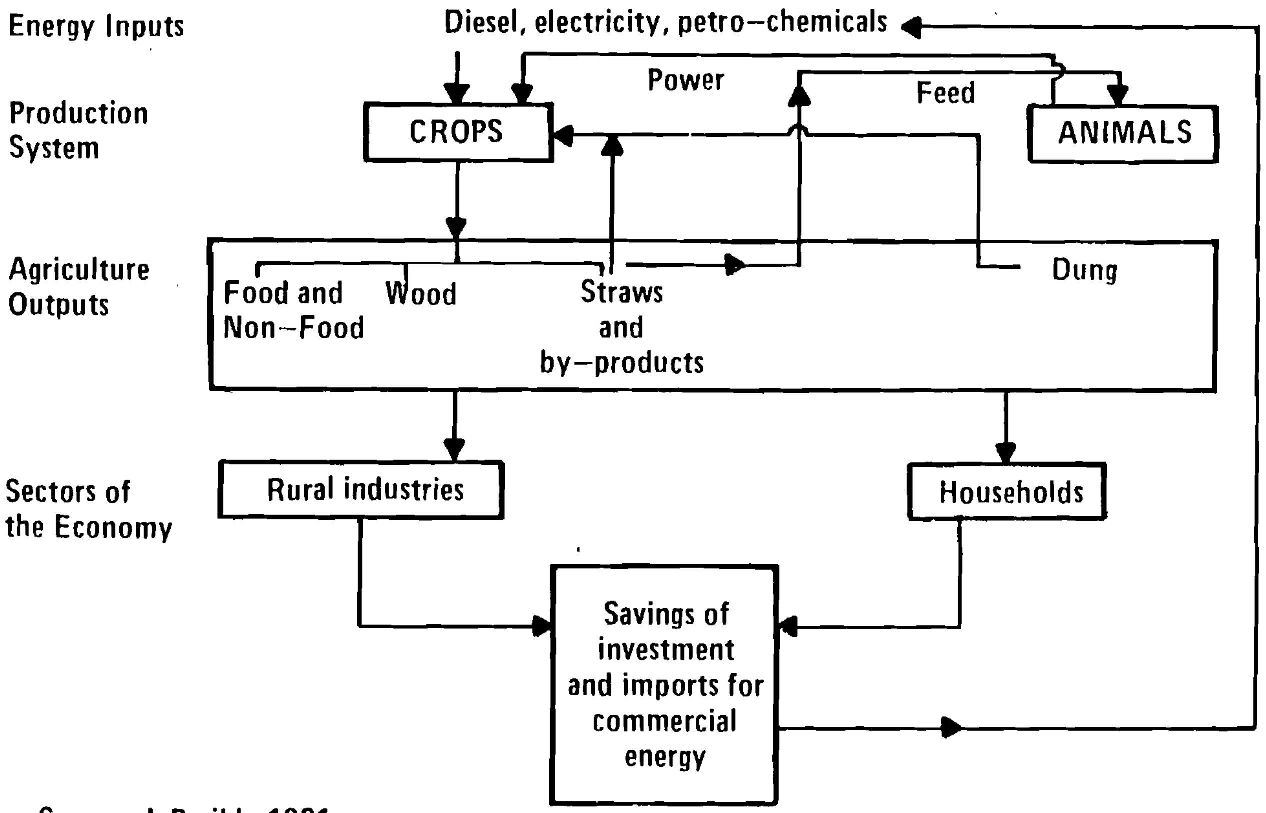
Energy is an important resource for agriculture and at the same time agriculture is a resource for energy. The present paper considers this relationship with regard to the developing countries, for which both these linkages are important. Depending on the country, 30% to 70% of the intermediate input costs of agricultural crop production are directly or indirectly related to energy; however, agriculture provides 20% to 90% of primary energy through the supply of noncommercial energy (wood, waste, dung, etc.). This interactive system of energy and agriculture is shown in Fig. 1. It can be seen that while some dung and residues are used by the agricultural sector itself in the form of fertilizer and feed, the rest is used as an energy resource in unprocessed form in rural households and rural industries. This leads to savings of investment and of imports that would otherwise have been required to obtain commercial energy. The savings may be used to purchase more "processed energy" (fertilizers, diesel oil, pesticides, etc.).

Socio-techno-economic factors intertwined with the energy-agriculture systems are as follows:

a) In rural agricultural systems, the animal dung and straws from crop-residues are used for household cooking, linking the household energy sector very strongly to the fertilizer question. It is appropriate to mention here that a number of countries obtain nearly 90% of household energy from non-commercial energy sources, i.e. wood, crop residues and animal dung. Figure 2 shows the contribution of non-commercial energy sources in total primary energy consumption for a few countries.

Figure 1.

ENERGY FOR AND FROM AGRICULTURE



Source: J. Parikh, 1981

Figure 2.

PERCENTAGES OF NON-COMMERCIAL ENERGY IN TOTAL ENERGY IN SELECTED DEVELOPING COUNTRIES (1978)

Chile Argentina Egypt	Malaysia	Colombia Brazil	Philippines Pakistan India Zimbabwe	Guatemala El Salvador Thailand	Sri Lanka	Bangladesh Mozambique Kenya Ghana	Zaire Sudan	Nepal Tanzania Ethiopia
10–20	21–30	31–40	41–50	51–60	61–70	71–80	81–90	91–95

b) The working cattle consume straws and waste but provide services such as ploughing, irrigation, transport, for which capital- intensive equipment such as tractors, pumps and trucks would otherwise be required. However, unlike these machines which consumes fuels, bullocks actually produce energy, i.e. dung. Thus, this brings into question the services and energy produced by the working animals and services provided by machines and their energy and capital requirements. The proportion of working animals in total animals ranges from 30% to 50% in developing countries of Asia.

c) Nearly 20% to 70% of total fertilizers applied come from organic fertilizers. However, the share of organic fertilizers is rapidly declining. The growth of organic fertilizers depends upon cattle population which provides the most significant share of manure. In some developing countries, like India, cattle population has nearly stabilized, and in some countries there is an annual growth of 1% to 3% at most. This is because of the simple reason that cattle requires large amounts of biomass to sustain itself and exerts pressure on scarce land for its feed. Moreover, there is an emphasis of improving quality - more meat, milk, services - rather than increasing number. Thus declining cattle growth and high growth rates in chemical fertilizers result in a declining share of organic fertilizers. As can be seen in Table 1, in most developing countries, even after 1973, the annual growth rates for the chemical inorganic fertilizer demands in many of the developing countries ranged between 6% to 17%. Yet, in absolute terms, the amounts applied per hectare (ha) are small - hardly exceeding 100 kg/ha and sometimes less than 15 kg/ha. Therefore, a clearer understanding on issues related to choices of fertilization is necessary.

d) Next to fertilizers, irrigation is the most energy-intensive operation, especially in Asian countries. The *timing* of availability of water is most crucial for irrigation. This question then is directly concerned with adequate and timely supply of electricity, diesel or animal power. The provision of peak demand for irrigation is one of the major problems for farmers, utility planners and oil- supply planners.

e) Linked with the above matters is also the fact that nearly 70% to 90% rural population survives on agriculture in an environment where infrastructure of transport and services is weak. This makes it difficult for commercial fuels such as kerosene, diesel and electricity to reach the rural areas making "self-sufficiency" one of the important rules for selecting production

Table 1. Consumption of fertilizer per capita and per hectare of arable land and land under permanent crops, and the annual average compound growth rate of these indicators, 1970-1978 (kg of nutrients).

	Consumption per capita			Consumption per ha		
	1970	1978	Annual compound Growth rate (percentage)	1970	1978	Annual Growth rate (percentage)
Afghanistan	1.1	3.5	15.6	2.4	9.0	18.0
Bangladesh	2.1	4.5	10.0	15.7	41.4	12.9
Burma	0.8	2.5	15.3	2.1	8.5	19.1
China	5.4	10.0	8.0	33.5	94.0	13.8
India	4.0	6.8	6.8	13.2	26.7	26.7
Indonesia	2.0	5.1	12.4	13.1	44.9	16.6
Iran	3.3	8.0	11.7	5.9	18.0	15.0
Malaysia	...	28.6	6.3	53.9	57.1	0.7
Nepal	0.5	1.7	16.5	2.7	10.1	17.9
Pakistan	4.7	11.4	11.7	14.6	44.1	14.8
Philippines	5.3	6.5	2.6	28.8	38.5	3.7
Sri Lanka	7.5	9.4	2.9	47.3	62.5	3.5
Thailand	2.3	6.4	13.6	5.9	16.5	13.7
Total Asia (1970-1978)	5.7	9.6	6.7	25.1	52.3	9.6
Total World (1970-1978)	18.8	25.0	3.6	46.6	75.4	6.2

Source: FAO Fertilizer Yearbook, 1974-1979.

... Figures not available.

technology.

These issues and a brief outline of such a model was proposed earlier and is now formulated in detail.

1.2. Energy for Agriculture

The extent to which each sector is detailed depends on the importance of the sector, i.e. mechanization, irrigation, fertilizers and pesticide application. Table 2 shows the direct and indirect energy uses of agriculture by the developing countries in different world regions.

In the developing countries the respective percentages for these energy uses are 26%, 14% and 60%. In Southeast Asia specifically, they are 13%, 20% and

Table 2. Percentage distributions of direct and indirect uses of commercial energy in agriculture.

Region	Energy in Agriculture in 10^9 j	Percentage Distribution			
		Fertilizers	Mechanization	Irrigation	Pesticides
Africa	2	53	42	3	1.6
South East Asia	20	66	13	20	0.5
Latin America	11	48	46	4	1.6
China	15	71	9	16	4.3
Developing Countries	49	59	26	14	1.0
Developed Countries	214	39	57	2	0.9
World	260	45	50	4	1.0

Source: Energy for World Agriculture, B. Stout et al., FAO

66% respectively. Thus fertilizer production makes the largest single use of energy for agriculture. (Pesticides, if separately accounted for, use 1% to 4% out of a total of 60%.)

1.3. Energy from Agriculture

As discussed earlier, agriculture provides a large percentage of rural energy, and therefore enters the modeling work in two ways:

- through the selection of crops and livestock which also produce primary energy resources as byproducts
- through activities that further process agricultural residues in their primary energy forms in order to obtain more processed secondary energy forms through conversions, such as bio-gas, charcoal or gasohol.

Thus the model would consider using primary energy inputs directly as well as processing part of these to obtain more efficient forms of secondary energy. When the above energy sources are insufficient, commercial energy is purchased.

1.4. Problem Statement and Problem Boundaries

A model is formulated to discuss several of the following issues relevant for policy:

- What could be the cropping allocation patterns in the future if the different amounts of nutrition and energy that crops and crop residues provide are considered along with the different levels of inputs required per hectare?
- How much land of various types (woodland, forest land and fallow arable land) can be allocated to energy crops (wood, cassava and sugar cane for gasohol, etc.) when land is also needed to produce food crops?
- What are the effects of energy prices on choices of farming technology?
- What are the food-fodder-fuel-fertilizer relationships in rural areas of developing countries? How precariously balanced are they and how sensitive are they to external forces and perturbations?
- What are the variables and parameters governing the decisions between organic and inorganic fertilizers, e.g. their upper limits energy prices, their nutrient values, etc.
- What is the agricultural importance of working animals which provide manure and small-scale draft power, but consume crop residues and feeds? What are the relative merits of bullocks and tractors for various classes of farmers having different amounts of landholdings, capital availability, etc.?
- To what extent can energy production from agriculture save net energy imports?
- *Timely* availability of electricity, diesel or animal power is very crucial for ground-water irrigation. What are the problems in meeting this highly peaked demand for farmers and energy-planners?

These and other issues can be examined in such an integrated system-analytic modeling framework.

The model is developed to understand the structural and dynamic aspects of the rural energy system that exists presently and thereby simulate the implications of various policy measures on the present system with its income groups and their assets - land, animals, tractors, etc. Because of this objective, distant future scenarios are not projected and capital acquisition module is not constructed though existing capital stock is given.

The model developed here is to be eventually linked to a detailed model of Bangladesh Agricultural Policy Model (BAM) being developed at the CWFS in the Netherlands. BAM, a year by year simulation model of the computable general equilibrium genre which distinguishes different types of farmers as well as labor and animal inputs by months. Cropping pattern decisions as well as asset accumulation decisions are also endogenous in the model. In particular, with the inclusion of investment decisions, the model should be more appropriate for a look at medium term options and policies and the dynamics of change in the system. For the present, the effort is restricted to understanding the behavior of the existing system under some changes.

2. MODEL DESCRIPTION

A linear programming model is constructed in order to capture interactions between

- crop and livestock production
- organic and inorganic fertilizers
- commercial and non-commercial energy used in rural areas of developing countries in the household, agriculture, and rural industries sectors.

The objective function is to maximize the revenues from crop and energy production. The model takes into consideration:

- several crop commodities
- 12 activities of energy production and purchase (these include the production of primary and secondary energy products e.g. charcoal, bio-gas, and gasohol, and final energy purchase)
- six activities of irrigation methods
- 12 activities of fertilizer provision (for these types of nutrients; nitrogen-, phosphorus-, and potassium-based, four distinct activities, viz. purchase of chemicals, bio-gas, manure and crop residues)
- four activities of draft power, including two types of tractors and two types of animals

- monthly requirements of labor, water and draft power, and availability of crop residues
- requirements for food and energy by income class, and aavailability of land and other resources such as tractors, draft animals, or cash

In addition, the model has the flexibility of introducing several land classes and/or subregions. Energy demand for cooking, lighting, and village industries are considered in competition with energy demand for agriculture.

The model is general and applicable to many of the low-income developing countries but would require different approximations and of course, input data depending on the data availability and characteristics of the selected country.

The motivation behind the objective function and construction of each module is discussed below.

3. OBJECTIVE FUNCTION

For a given rural area, we maximize the revenues from crops minus the costs of purchasing fertilizers, commercial energy, feed and hired labor. The crops are selected according to the agro-climatic conditions and its initial pattern is given as the one that exists presently. Livestock is assumed to be given as present and its maintenance is imperative.

maximize for the rural area

$$\sum_j \sum_c \left\{ \underbrace{y_{cj} * L_{cj} * p_c}_{\substack{\text{yield} \times \text{area} \times \text{price} \\ \text{revenue from crops}}} - \underbrace{\sum_n p_n * B_{n,j}}_{\substack{-\text{ cost of bought} \\ \text{nutrients}}} - \underbrace{\sum_k p_k * B_{k,j}}_{\substack{-\text{ cost of bought} \\ \text{energy}}} - \underbrace{\sum_f p_f * B_{f,j}}_{\substack{-\text{ cost of bought} \\ \text{feed}}} - \underbrace{w * [H_j - H_{ownj}]}_{\substack{-\text{ cost of hired} \\ \text{labor}}} \right\}$$

j = income class index; c = crop index; n = index for types of nutrients

k = index for energy sources

y_{cj} = Yield of crop c by income class j in tons per hectare (ha)

L_{cj} = Land area under crop c by income class j in 1000 ha

p_c = Price of crop c per ton

p_n = Price of ton of fertiliser of type n

$B_{n,j}$ = Bought nutrients in tons by class j

p_k = Price of bought energy (kerosene, diesel, electricity) per physical units (kilolitres, or 1000 kwh)

$B_{k,j}$ = Bought energy in physical units by class j

p_f = Price of bought feed per ton

$B_{f,j}$ = Bought feed in 1000 tons by class j

w = Wage rate per day

H_j = Total human labor days required by class j

$H_{o,j}$ = own labor days put in by class j

Notice that due to weak infrastructure in the rural areas only the purchased commodities from outside of the rural areas are minimized in the stated objective function. However, the objective function could be varied depending on the viewpoints. For example, one may wish to minimize the use of non-commercial energy sources explicitly and consider their prices here. The maximization is subject to the constraints of resource availability, individually as well as collectively. For example, each income class has private assets such as land, livestock, etc., as well as access to the collective resources such as wood resources, or unused biomass resources from other income classes such as dung and crop-residues which are exchanged freely. In reality, while most often some of the non-commercial energy resources are gathered, obtained in return of farm labour or goods, or given away, there are some instances when these are actually done with cash. It will be shown later that energy sources such as bio-gas, charcoal or ethanol, are also considered in this static model. The discussions on the constraints, assumptions and technical coefficients are given below and equations for constraints are given in the Annex.

4. CROP PRODUCTION AND CROP RESIDUES

Each income class has fixed amounts of land and also broad allocation of crop-production, which is assumed to be given. The yield-fertilizer responses are assumed to be given.

The crop-residue coefficients for each selected crop are given exogenously. Thus, on the basis of yield, land allocation and crop residue coefficients, crop residues are generated separately for each income class. They could have the following uses:

a) Feed for the cattle, working animals, etc.

b) Fuel for household cooking by different income class

c) Fertilizer for farms with or without burning

d) Other purposes such as construction, handicrafts, mats, furniture stuffings, etc. to be given exogenously.

The last is given exogenously as a percentage of total. All residues from different crops are added for a given income class j which allocates them to the above uses depending on his requirements and other opportunities.

5. LIVESTOCK: MAINTENANCE AND SERVICES

The livestock module consists of the feed and human labor requirements for the animals, dung production and its use by various income classes and the services provided by the working animals. Only cattle and buffaloes are considered in the model because they have high feed requirements and also highly volatile dung production and they provide services. Thus, horses, sheep, goats, etc. are not considered. The number of animals and their distribution between various income classes are considered to be exogenously given. For service purposes the equivalent animals are calculated by using equivalence principle:

2 cows = 1 bullock = 1/2 buffalo.

Meat, milk and other products given by animals are not considered because of the limited objective of studying energy-related issues. The following are the activities related to livestock.

5.1. Maintaining Working and Non-working Animals

a) Feed requirements: Feed which is required in addition to that obtained from pastures (approximately 30% of the requirements) could be obtained from crop-residues and when that is not sufficient, the feed could be bought. The calorie and protein contents of the individual feed have to be greater or equal to the required calories and protein by the animals.

b) Human labor: In addition to feed, maintaining animals requires human labor.

5.2. Dung Production and Its Uses

The availability of dung for both types of animals is considered along with the collection coefficient which is generally smaller for working animals. This could be used by each income class from the livestock it has as follows:

a) For cooking in the household*

b) As manure in the farms

c) As input in the biogas plants

5.3. Machinery vs. Services Provided by Working Animals

Working animals provide three types of services: Ploughing, transport and irrigation. Note that the model is meant to run only for short or medium term, so investment decisions are not made in the model. What is explored is the behavior of the farmers in the short run.

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*Although only the nitrogen is lost while burning, and P and K remain in the ashes, very often the ashes are not carried back to the fields and used up for cleaning utensils.

a) Ploughing: Ploughing could be done by animals or by (several types of) *tractors whose stock is given a priori.* Each requires different amounts of human labor days, animal labor days and diesel consumption per hectare of ploughing.

Table 3. Comparison of resource requirements for the services provided by working animals with equivalent machines in Bangladesh.

Services	Units	Human Labor Days	Animal Labor Days	Machine Days	Diesel Liters
Ploughing	per ha				
1. Animals		11	20	0	0
2. Light Tractors		3.5	0	3	4
Transport	per 100 ton-km + empty trips				
3. Animals		14	22	0	0
4. Trucks		1.5	0	0.75	10
5. Tractors	3.0	0	2.5	20	

3) Assuming a pair goes at 4km per hour for 8 hours for pulling 0.5t weight and 8km per hour for empty trips (40km). Human labor days are 50% of total days + time required for maintenance.

4) Assuming a truck has 3 to 5 ton capacity, going at 25km per hour and 50% empty trips (only 12.5km).

5) Assuming tractor carries 1 to 2 ton, goes at 10km + 50% empty trips.

Note that the share of empty trips gets larger for vehicles with smaller capacity. In selecting velocity, bad roads of the rural areas have to be kept in view. Each of the above includes loading and unloading time.

b) Transport: Agricultural surplus is transported to nearby places by bullocks, trucks and tractors whose stock is given. Each requires different amounts of human labor, machine time, animal labor and diesel.

c) Irrigation: Irrigation could be of two kinds: surface and ground-water. These again could be divided into many appropriate methods, such as diesel and electric pumps, tubewells, handpumps, etc. It is important to know the upper limits for possible supply from each along with capital costs, labor and energy-use for supplying water for each of the technologies selected. Irrigation is considered in the model only to account for magnitudes of the energy requirements. Choices among different technologies are not made within the model but are given a priori from the known data and their resource requirements such as human and animal labor, machine time, diesel consumption etc. are accounted for.

The coefficients used are given in Table 3. The constraints of meeting the demand must be satisfied for each month, or better, periods smaller than a month (e.g. 10 days) so as to avoid allocating off-season time to the sowing, or harvesting season.

6. FERTILIZER SECTOR

The levels of fertilizer application in terms of kg/ha for N, P and K are exogenously given corresponding to the yield level desired by each income class.

There are four ways of obtaining fertilizers:

a) By using crop-residues, i.e. burning or ploughing back straws on the ground

b) By using dung

c) Using bio-gas sludge

d) Purchasing chemical fertilizers.

The first three of these are organic fertilizers.

The nutrient contents of organic fertilizers are given in Table 4.

Table 4. Nutrient contents of organic fertilizers (on a dry matter basis).

	N	P	K
Crop residues (kg/ton)	2.5	0.8	0.7
Dung (kg/ton)	10.0	5.0	12.0
Bio-gas sludge (kg/1000m^3)*	16.0	14.3	10.0

*1000m^3 bio-gas requires animal dung and generates sludge which is considered here in dry matter.

However, recall that the objective function minimizes only purchased commodities. Therefore, depending upon the relative prices of bought fuel, fodder and fertilizers, and the demand for each, the choices of how much bio-materials get used for what purpose are made. Shortfall is made up by the purchased fertilizers.

7. ENERGY FROM AGRICULTURE

7.1. Energy Supply Side

Energy module considers 12 different types of energy sources used in households, rural industries and agriculture. They are classified in three categories.

a) Non-commercial energy which is gathered or produced within the agricultural system, such as wood, dung and crop residues

b) Secondary energy after the conversion processes are carried out on non-commercial energy (see Figure 3).

c) Commercial energy that is purchased, such as kerosene, diesel, electricity or natural gas.

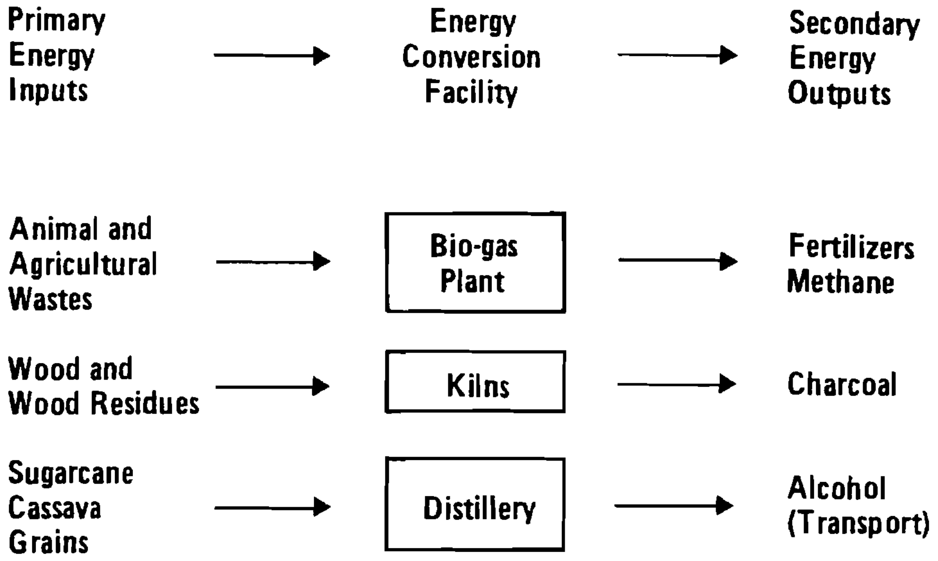

Figure 3. Secondary and Primary Energy Sources Obtained from Agriculture.

The manner in which each of them is treated is discussed below. The distinction is made by income class if the production is controlled by the user. For example, bio-mass use is included in the first category which is directly used by the consumer without processing. The 12 energy sources are treated as follows:

i) Crop-residues: As mentioned before, production of each crop is multiplied by the crop-residues it produces. Since each income-class has its own control on how to use them, this energy source (or fertilizer source) is treated for each income class separately . Having produced the crop already, obtaining residues costs only labor.

ii) Animal dung: For two categories of cattle--working and non-working cattle--two different dung coefficients are taken and two different collection coefficients. A working animal, which is also a strong adult, eats 30% to 50% more than non-working animals, more than 50% of which are calves. Thus, the dung output of a working animal is higher, but on the other hand, collection coefficient is low, because they are not stall-bound.

Three categories of wood are considered fuelwoods.

iii) Fuelwood 1: In this category, the supply is gathered from homesteads (clusters of trees within houses) requiring only labor. The upper limit of wood is estimated from the area under them and its productivity. The heat values of twigs, branches and barks are low.

iv) Fuelwood 2: The supply is obtained by employing human labor from natural forests. Its upper limit is specified by the are under forests multiplied by productivity. The heat value of forest wood is higher than dry matter collected around homesteads.

v) Fuelwood 3: This is harvested from wood plantation which are grown commercially requiring investment, management and perhaps transport. The heat value of this wood is the highest.

The above-mentioned bio-fuels could be processed through conversion facilities to obtain more efficient and high valued energy forms. A schematic version is illustrated in Figure 3. These energy forms require initial investment but in this static model they are considered after deriving their annual costs, assuming certain rate of return (10%). A selected few secondary energy froms obtained from bio-fuels are as follows:[*]

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[*] The revised model also incorporates family ($2m^3$), homestead level ($10m^3$), and village level ($100m^3$) bio-gas plants; pit kilns, brick kilns, portable metal kilns for charcoal and sugarcane, cassava and corn distilleries.

vi) Bio-gas plants: Cattle dung could be converted to bio-gas (methane) by anaerobic digestion process. The residue bio-gas sludge could still be used as fertilizer nutrient (values for which are shown in the fertilizer sectors). Thus, it allows manure to be used as more efficient energy form as well as retains the possibility of using the sludge as fertilizer. The annualized price is, however, high because its capital cost is nearly Dollar 250 for a 2 m^3/day plant. It requires 6 tons of dung for 1000 m^3 of gas production.

vii) Charcoal kilns: For industrial purpose and for urban cooking requirements, charcoal is often a preferred fuel because it burns more efficiently and contains more energy per unit weight and therefore is more easily transportable. However, it requires 6 tons of wood per ton of charcoal and the kilns cost nearly 500 Dollars. However, when the wood supply from forests is high, (which is not the case in Bangladesh), this could be a practical solution for supplying transportable and efficient energy source.

viii) Alcohol: When sugarcane or cassava production is high and the nation is "rich" enough to demand gasoline, an ethanol distillery could be set up to convert biomass into alcohol. This option is especially appropriate for nations who are agriculture-surplus and energy-deficient. The demand for gasoline should be exogenously specified in the model, part of which could be satisfied by products from crude oil refineries and the remainder from alcohol.

i)-xii)Commercial energy forms: Purchased energy

Kerosene, diesel, natural gas and electricity come into this category. They are usually brought into rural areas from urban areas. In the rural energy model they are purchased only in the absence of other fuels, partly because their availability in the rural areas is a constraint because of the poor distribution system and partly due to inability of rural population to pay for them with cash.

These twelve categories of fuels are used by three sectors, i.e. households, rural industries and agriculture, with different efficiencies, details of which are discussed below.

7.2. Energy demand side

a) Household sector (excluding gasohol and diesel).

This includes all households, split into different income classes, in rural and urban areas. The energy used by rural households is assumed to be mainly for cooking and lighting. All fuels except gasohol and diesel could be used for cooking. They are all measured in terms of useful energy, i.e. primary energy contents multiplied by efficiencies with which they are used. For lighting, only three sources are considered: kerosene, bio-gas and electricity are used. However, since the quality of light by each source is different, rather than using "useful energy concept" in the case of lighting, one merely asks: How many units would be required annually by a household if the lighting is done by only a particular source? The values taken for the three sources (for Bangladesh) respectively are: 25 litres of kerosene, 220 m^3 of bio-gas or 160 kWh of electricity. However, it should be noted that in the present conditions in most rural areas of developing countries, the use of kerosene lamps for lighting is common.

The role of food-processing, in particular, parboiling paddy, boiling milk, etc., is quite significant, but because of inadequate data it is assumed that household energy demand surveys include this component within cooking.

b) Village industries sector: (Uses primarily wood, kerosene, electricity and diesel).

This could include food processing industries outside the households, such as bakeries, flour mills, rice mills, etc., and industries for dyeing, printing, metal working, repair shops, etc. The demand is calculated on an aggregate basis based on coefficient of energy per unit value added in non-agricultural sector.

c) Agriculture sector (including diesel and heavy oil and electricity).

This includes energy use for tractors, irrigation pumps, trucks and competition of each use for activities such as ploughing, transport and irrigation are considered with other methods such as by animals, humans or others.

The primary energy efficiencies for each of the fuel for each sector are given in Table 5.

Table 5. Energy sources considered in the model, primary energy contents and assumed efficiencies for household cooking and village industries.

Energy Forms	Unit	Primary Energy in GJ per Unit	Household Cooking Efficiencies		Village Industry
			Low	High	
Crop residues	ton	12.6	0.10	0.150	0.12
Dung	ton	13.8	0.09	0.137	-
Fuelwood 1 (homesteads)	ton	15.0	0.11	0.165	0.12
Fuelwood 2 (forests)	ton	17.0	0.11	0.165	0.15
Fuelwood 3 (plantation)	ton	18.0	0.15	0.225	0.20
Charcoal	ton	29.0	0.25	0.35	0.25
Biogas	$1000m^3$	25.4	0.55	0.55	-
Gasohol	kilo lit.	36.0	-		-
Natural gas	$1000m^3$	35.0	0.60	0.70	0.70
Kerosene	kilo lit.	35.0	0.35	0.50	0.20
Electricity	1000 kWh	3.5	0.65	0.75	0.60
Diesel	kilo lit.	35.0	-		-

8. CONCLUDING REMARKS CONCERNING APPLICABILITY OF THE MODEL

A general model to explore rural energy systems or issues concerning energy for and from agriculture in a developing country is developed to obtain insights into behavior of several income class categories. Model equations are given in the annexure. Since the application to Bangladesh was envisaged before the model was formulated, the model is more detailed to suit the conditions of Bangladesh. Therefore, it may require modifications, if applied to other countries depending on the characteristics of the country.

As shown in Table 2, different issues have priority for different world regions and for different countries. Choices of fertilization and irrigation are more important compared to mechanization in Asian countries. Therefore, less disaggregation in mechanical equipment may suffice in Asian countries compared to, say, Latin America, where less choices of irrigation may be required compared to choices of mechanization. Thus, the extent of detailing required for different choices may vary for different countries if the general model presented here were to be used.

Similarly, depending on the country, importance of animal power, or alcohol, or charcoal production etc. may have varying degrees of relevance. Thus, in the case of Brazil, the model would have to be detailed to include more distilleries for varieties of alcohol and vegetable oil. In India's case, for example, the problem worrying the planners is month-wise electricity and diesel requirements for irrigation purposes. However, for proper evaluation of alternatives, investment and outflow streams (rather than annualized investments) need to be taken into account for which the model needs to be dynamic. Efforts in this direction are underway. As we shall see later, it so happens that in the case of Bangladesh the bio-mass allocation for food, fodder, fuel and fertilizer is the most crucial question that is being picked up in the application that is carried out. This factor is also relevant for some provinces of China and India.

Annexure: Mathematical Description of the Model

Code to the Symbols

1. Activities are in capital letters
2. Running Index is indicated by subscript
3. Identification Index is indicated by superscript
4. Coefficients are in small letters

Indices

m	month index
c	crop index
j	income class
b	animal types
f	feed
p	power types for cultivation
t	transport types
n	nutrient index
k	energy index

Activities, Resources, Agents and Units

Index	Unit	Text
c=		crop type
1		wheat
2		rice
3		jute
j=		income class
1	1000	small farms
2	1000	middle farms 1
3	1000	middle farms 2
4	1000	large farms
5	1000	very large farms
6	1000	landless
m=		month (12) m=1, January
b=		animal type
1	1000 head	not working
2	1000 head	working
f=		feed from crop residues
1	1000 t	bought feed (grains, etc.)
2	1000 t	feed from pasture
n=		fertilizer type
1	ton	N
2	ton	P
3	ton	K

i=	irrigation
1	canal
2	tubewell diesel
3	tubewell electric
4	animals
5	handpump
6	other manual

k=		energy B=purchased, Q=produced
1	1000 kg	crop residues
2	1000 kg	dung
3	1000 kg	fuelwood from homesteads
4	1000 kg	fuelwood from forests
5	1000 kg	fuelwood from plantations
6	1000 kg	charcoal
7	1000 m^3	biogas
8	1000 l	gasohol
9	1000 m^3	natural gas
10	1000 l	kerosene
11	1000 kWh	electricity
12	1000 l	diesel

p=	power source for cultivation
1	animals
2	tractors

t=		vehicle type
1	number	bullocks
2	number	tractors
3	number	trucks

Note: The model could be run month-wise or annually. However, only the first constraint is illustrated with symbol m. In the rest of the equations, symbol m is dropped for convenience (except in the case of ploughing and irrigation).

Set of constraints on the objective function:

1. Crop residue balance

r_c = crop residue from crop c in t of dry matter per ha. Symbol r denotes crop residue.

f^r_{cb} = feed required in 1000t of dry matter from crop residues per year by 1000 heads of animal type b.

N^r_{cmj} = crop residue in 1000t of dry matter used directly as nutrients in the fields for crop c in month m by class j.

F^r_{cmj} = crop residues in 1000t of dry matter used as feed in month m by class j.

O^r_c = crop residues in 1000 t used for other purposes and village industries.

L_{cmj} = land in month m for crop c in 1000 ha by income class j.

A_{bj} = animal type b 1000 heads owned by class j.

Q^r_{cmj} = crop residues for crop c in 1000t used for burning by month m by income class j.

$F^r_{cj} = \sum_b f^r_{cb}\ A_{bj}$ = feed for animals from crop residues.

Crop residues are available only in the months of harvest. (However, the application of the model is only done annually and not month-wise).

$$\underset{\substack{\text{crop res.}\\\text{production}}}{-y_{cmj} * L_{cmj} * r_c} + \underset{\text{feed}}{F^r_{cmj}} + \underset{\text{fields}}{N^r_{cmj}} + \underset{\substack{\text{house-}\\\text{holds}}}{Q^r_{cmj}} + \underset{\substack{\text{other}\\\text{purposes}}}{O^r_{cmj}} \leq 0$$

This is for each income class j. r labels residues.

Total use of crop residues by all income classes = Q_1

$$\sum_j \sum_c \sum_m Q^r_{cmj} = Q_1$$

(See para.6a.)

2. Animal feed balance: f

$(cal)^B, (prot)^B$= calorie and protein coefficients of bought feed in 10^9 kcal and 1000 t of feed.

B^f Bought feed in 1000 t.

f^{cal}_b, f^{prot}_b is calorie and protein requirement per year for 1 animal in 10^6 kcal and t respectively.

A_b = 1000 animal heads of type b

$(cal)^r$, $(prot)^r$ calorie in 10^6 kcal/t and protein in t/t of crop residues.

Fixed amounts of $(cal)^{past}$ and $(prot)^{past}$ are obtained from grazing in pastures.

Calorie balance:

$$-(cal)^{past} - (cal)^b - B^f - (cal)^r * F^r + \sum_b f^{cal}_b * A_b \leq 0$$

Protein balance:

$$-(prot)^{past} - (prot)^b * B^f - (prot)^r * F^r + \sum_b f^{prot}_b * A_b \leq 0$$

$$-pastures\ -purchased\ feed\ -crop\ residue\ +requirements \leq 0$$

This is for each income class j. f labels animal feed.

3. Animal dung balance:

d_b dung in dry matter (d.m.) per year in 1000 t per 1000 animals of type b.

c^d_b fraction of d_b that gets collected or gathered.

Q^{db}_j bio-gas produced from dung in 1000 m^3 per year.

N^d_j dung in t of d.m. that is used directly as manure.

Q^d_j dung used in households by jth income class for cooking in t.

e_b^d tons of dung required for 1000 m^3 of bio-gas.

$$-\underbrace{\sum_b c_b^d d_b A_{bj}}_{\text{collected dung from animals}} + \underbrace{N_j^d}_{\text{Manure}} + \underbrace{e_b^d Q_j^{db}}_{\text{bio-gas}} + \underbrace{Q_j^d}_{\text{Household cooking by j-th income class}} \leq 0$$

Total dung used for cooking by all income classes = Q_2 .

$$\sum_j Q_j^d = Q_2$$

(See para.6a.)

This is for each income class j. d labels animal dung.

4. Fertiliser-nutrients balance:

$(nut)^{d,n}$ nutrient of n type in t per 1000 t of dung.

$(nut)^{r,n}$ nutrient of type n in t of d.m. per 1000 t of crop-residues.

$(nut)^{b,n}$ nutrients of type n in tons from 1000 m^3 of bio-gas.

F_{cj}^n applied fertilisers on crop c by class j in t.

B^n purchased chemical nutrients in t.

$$N_{nj}^b = Q_j^{db} * (nut)^{b,n}$$

N_n^d , N_n^r , N_n^b , B^n are activities of fertilising with dung, crop residues, bio-gas sludge and bought chemical fertilisers.

$$\underbrace{\sum_c F_{ncj}}_{\text{Applied fertilizer}} - \underbrace{B_j^n}_{\text{bought chemical fertilizer}} - \underbrace{(nut)^{d,n} N_{nj}^d}_{\text{manure}} - \underbrace{(nut)^{r,n} * N_{nj}^r}_{\text{crop residues}} - \underbrace{N_{nj}^b}_{\text{bio-gas sludge}} \leq 0$$

The equation is repeated for each type of nutrients N, P and K, i.e.

n = 1, 2, 3 = N, P, K respectively.

5. Irrigation methods

Six methods of irrigation are considered.

i = 1 Animals

2 Tubewell-diesel

3 Tubewell-electric

4 Canal (gravity)

5 Handpump

6 Other – manual or not irrigated

Note: This part of the model is computationally included only partially to account for energy, human labor and animal labor requirements as this might conflict with other uses. Thus, it is only included in resource requirements such as diesel, electricity, human labor and animal labor in fixed proportions.

Choices of methods are not considered in the model, but fixed proportions are assumed. However, care is required to specify the demand month-wise so as to deal with the policy issues of peak demand for electricity, animal power and diesel distribution often worrying the farmers and planners. For larger countries, the demand would have to be also region-wise.

Moreover, upper limits for each type of irrigation methods in terms of area have to be given.

6. Energy balances for uses of energy:

Q_k = Energy production and purchase activities which are separate from utilisation of it

k = energy sources. Production activities in physical units u(k)

1 = crop res. in t

2 = dung in t

3 = fuelwood gathered from homesteads (only labor costs) in t

4 = fuelwood from forests (high transport costs) in t

5 = fuelwood from wood plantations (requiring investment, fertilisers, irrigation, labor) in t

6 = charcoal in t

7 = bio-gas in $10^3 m^3$

8 = gasohol in 10^3 l

9 = natural gas in $10^3\ m^3$

10 = kerosene in 10^3 l

11 = electricity in 1000 kwh

12 = diesel in 10^3 l

6(a) Household cooking (for j income classes)

$$\sum_{k=1,12} -u_k^h * Q_{kj}^{ck} + u_j^{ck} \le 0$$

$$\sum_j Q_{kj}^{ck} = Q_k$$

u_k^h useful energy for energy source k in household cooking in 10^{12} J/u(k)

u_j^{ck} cooking energy requirements in useful energy 10^9 J per year by exp. class j.

Q_{kj}^{ck} physical units of energy source k in u(k) used in cooking by class j.

$u_k^h = (eff)_k^h * e_k$

where

$(eff)_k^h$ is efficiency with which energy source k is used in households

e_k is primary energy contained in energy source k in 10^{12} J/u(k).

6(b) Rural lighting

$$\sum_{k'} - u_{k}{'}^{1} * Q^{l}_{k'j} + u_j^{light} \le 0$$

$k' =$ 7, 10, 11 bio-gas, kerosene and electricity.

u_j^{light} demand for lighting for exp. class j.

$u_{k}{'}^{l}$ effective number of households that could be satisfied with 1000 units of k'.

(As the three sources give qualitatively different lighting, the formulation has been made in terms of persons' needs).

$Q^{l}_{k'j}$ activities of lighting with energy source k' by class j.

6(c) Energy budget constraint for households for cooking and lighting

$$\sum_{k'} p_{k'}(Q^{ck}_{k'j} + Q^{l}_{k'j}) \le b_j^h$$

$p_k{'}$ price of energy of type k per physical unit (mu/u(k))

b_j^h household budget for fuel and electricity for jth exp. class in 1000 monetary units

mu = monetary unit

6(d) Requirements for village industries

$$\sum u_k{'}^{VI} * Q_k{'}^{VI} \ge u^{VI} * Y^{VI}$$

u_k^{VI} = useful energy from each type of energy source utilised in village industries = $(eff_k^{VI} * e_k)$ in 10^{12} J/u(k)

Q_k^{VI} = quantities of energy used of type k by village industries in 10^3u(k)

y^{VI} = value added in 10^6 monetary units by village industries.

u^{VI} = useful energy in 10^{12}J/u(k) taka of y^{VI}.

k' excludes gasohol

$u_k^{VI} = (eff)_k^{VI} * e_k$

$(eff)_k^{VI}$ efficiency with which source k is used in village industries.

e_k is primary energy contained in source k in 10^{12}J/u(k).

7. Energy balance for each type of energy supply k

Crop-residue and dung balance equations already given previously stating also other purposes for which they are used.

7(a) Wood balance

$$\underset{\substack{\text{sum of}\\ \text{all households with}\\ \text{income class j}\\ \text{j,k=3}\\ \text{4,5 only}}}{\sum Q^{c}_{kj}} + \underset{\substack{\text{village}\\ \text{industries}}}{Q^{VI}_{5}} + \underset{\substack{\text{charcoal}\\ \text{production}}}{\frac{1}{(eff)_{ch}} Q_6} \le \underset{\substack{\text{wood from}\\ \text{homesteads,}\\ \text{plantations}\\ \text{and forests}\\ \text{k=3,4,5}}}{\sum Qk}$$

$(eff)_{ch}$ = conversion efficiency or amount of charcoal in t that could be obtained from 1 t of wood.

Bounds (in tons):

$$Q_4 \le Y_F * F, \quad Q_5 \le Y_P * P, \quad Q_3 \le Q_A$$

The wood obtained from forests and plantations must be less than the yield (Y_F and Y_P, respectively) area under forests (F) and plantations (P). The wood obtained from homesteads cannot exceed externally specified amount Q_A .

7(b) Charcoal balance (tons)

$$\underset{\text{cooking}}{\sum_j Q_6^{cj}} + \underset{\substack{\text{vill.}\\ \text{ind.}}}{Q_6^{VI}} \le \underset{\text{supply}}{Q_6}$$

$$Q_{6=charcoal} = (eff)_{ch} * Q_{wood,ch}$$

7(c) Bio-gas conversion (1000 l)

$$Q_j^{db} = Q_{7j}$$

Activity already discussed in eq.3 and eq.4.

7(d) Alcohol conversion (1000 l)

$$Q_i = \sum_m [y_{cmj} * L_{cmj} * r_{cm}] * \delta_c$$

δ_c = litres of gasohol produced from tons of crop residue of crop c where c could refer to sugarcane, cassava or corn.

7(e) Natural gas balance (1000 m^3)

$$\underset{\text{purchased}}{-B_{ng}} + \underset{\substack{\text{household}\\ \text{cooking}}}{\sum_j Q_9^{cj}} + \underset{\substack{\text{village}\\ \text{industries}}}{Q_9^{VI}} \le 0$$

Note: As natural gas is available only in the urban areas, this equation is excluded for the present study, which applies to Bangladesh.

7(f) Kerosene balance (1000 l)

$$\underset{\text{bought}}{-B_k} + \underset{\substack{\text{households}\\\text{cooking}\\\text{+ lighting}}}{\sum_j \left[Q^c_{10,j} + Q^l_{10,j}\right]} + \underset{\substack{\text{village}\\\text{industries}}}{Q^{VI}_{10}} \le 0$$

7(g) Electricity balance (1000 kWh)

$$\underset{\substack{\text{tube wells}\\\text{and pumps}}}{el_p} + \underset{\substack{\text{village}\\\text{ind.}}}{Q^{VI}_{12}} + \underset{\text{households}}{\sum_j (Q^{cj}_{11} + Q^{lj}_{11})} \le \underset{\substack{\text{bought}\\\text{from grid}}}{B_e} + \underset{\substack{\text{generated}\\\text{by diesel}\\\text{generators}}}{G_d}$$

where

el_p = electricity required in 1000 kwh for drawing 1000 ha-m of water by electric tubewells (te) given exogenously.

G_d = electricity generated in 1000 kwh from diesel generators.

7(h) Diesel balance (1000 l)

$$\underset{\text{pumps}}{d_p * \sum_{im} L_{mi}} + \underset{\substack{\text{village}\\\text{ind.}}}{Q^{VI}_{12}} + \underset{\substack{\text{tractor}\\\text{cultivation}}}{d_T * \sum_m L_{m2}} + \underset{\substack{\text{tractors and}\\\text{truck transport}}}{\sum_{t=2,3} d_t * (Tkm)_t} + \underset{\substack{\text{elec.}\\\text{gen.}}}{D_E} \le B_d$$

where

d_p = diesel required in 10^3 l for 1000 ha of irrigated land. of water.

d_T = diesel required in 10^3 l for 1000 ha ploughed by tractors.

d_t = diesel required for 1000 Tkm by tractors (t=2) and trucks (t=3)

D_e = G_d x 0.25 lit. (0.2 generates 1 kwh of electicity) in 1000 l.

B_d = bought diesel in 1000 l.

L_{mi} Land in 1000 ha to be irrigated by method i in month m. However, only method i=2 uses diesel.

L_{m2} Land ploughed with method 2 (i.e. tractors) in 1000 ha.

$(Tkm)_t$ see equation below.

8. Transport requirements (monthly basis)

t = 1 Bullocks
2 Tractors
3 Trucks

$\sum_m \sum_t (Tkm)_t \ge$ Demand for transport in 100 Tkm

≥ Marketable surplus * average distance

$$\geq \Big(\sum_{cj} y_{cj} * L_{cj} - \sum_j n_j^{rural}\Big) * a_d$$

= (Total production - self consumption in rural areas) * distance

a_d = assumed average distance of transport in kilometers

$(Tkm)_t$ = distance travelled by each mode t in 100 ton-kilometers (Tkm).

9. Animal power requirements (monthly basis)

$$\underset{\text{land preparation}}{\sum_p c_{mp} * L_{mp}} + \underset{\text{irrigation}}{a^w * w_m^1} + \underset{\text{transport}}{a_m^1 * (Tkm)_1^m} - \underset{\text{availability (monthly)}}{\sum_b a_b * A_b} \leq 0$$

where

c_{mp} = 1000 animal days for land preparation of 1000 ha with animals (p=1).

a^w = 1000 animal days per 1000 ha of irrigated land.

a_b = 1000 animal days per 1000 animal type b per month.

a_m^1 = animal days required for 100 Tkm.

L_{mp} = land ploughed in 1000 ha by power p (p=2).

10. Tractor power requirements (monthly basis)

$$\underset{\text{land preparation}}{c_{mp} * L_{mp}} + \underset{\text{transport}}{a_m^2 (Tkm)_2^m} \leq \underset{\text{monthly availability}}{T_m}$$

c_{mp} = tractor days for preparing 1 ha of land with tractor in m.

a_m^2 = tractor days for 100 Tkm in month m.

T_m = T/12 = total no. of tractors/12 months.

11. Human labor constraint (monthly basis)

H_m, O_m, M_m = monthwise labor availability, overwork and migration labor in days

h_{mp} = labor days for ploughing 1 ha by method p

L_{mp}, L_m = land in 1000 ha ploughed by method p or irrigated by method i

h_{mb} = labor days for maintaining 1 animal b

h_{mt} = labor days for 1 t km by method t

h_{mi} = labor days for irrigating 1 ham by method i

h_{mk} = labor days for producing or converting 1 u(k) energy type k

$$\underset{\text{– available labor}}{-(H_m + O_m \pm M_m)} + \underset{\substack{\text{ploughing}\\ \text{with types p}}}{\sum_p h_{mp} L_{mp}} + \underset{\substack{\text{irrigation}\\ \text{of types i}}}{\sum_i h_{mi} L_{mi}} + \underset{\substack{\text{maintaining}\\ \text{animals}\\ \text{of types b}}}{\sum_b h_{mb} A_{mb}} +$$

$$+ \underset{\substack{\text{energy production}\\ \text{of types k}}}{\sum_k h_{mk} Q_k} + \underset{\substack{\text{transport of}\\ \text{types t}}}{\sum h_{mt} (TKM)_t} \leq 0$$

12. Land identity

$$\sum_m \sum_p L_{mp} = \sum_c \sum_m L_{jcm} * (ci)_j = \sum_m L_{mi}$$

Total land ploughed= total land under crop = total land irrigated

$= \sum_j$ land owned by each class j * cropping intensity by j

PART II

APPLICATION OF THE MODEL TO BANGLADESH* Food-Fodder-Fuel-Fertilizer Relationships for Bio-mass

J. K. Parikh and G. Krömer

1. INTRODUCTION

Bangladesh provides one of the most relevant case studies for the application of the model described in Part I. In particular, the model could give insights into food-fodder-fuel-fertilizer relationships because it provides an example where limited biomass resources need to be stretched to fulfill conflicting demands on them.

It has one of the highest population densities in the world with 617 persons/km^2, i.e., 88 million over 144,000km^2, in 1979. 90% of the population lives in the rural areas where 93% of the household energy consumption is provided by biomass fuels, such as cow dung, straws, jute sticks, twigs, wood, etc. What is challenging about it is: How does a rural population of 73 million obtain food, fuels, building materials (dung, straw, sticks, mud, etc.) and sustain livestock from the scarce land it has? The present situation of Bangladesh may be of interest to other developing countries whose population growth is high and who may have similar population densities in the next three decades. In addition, the future of Bangladesh, whose population increases at 3% per annum from a high base of 88 million, itself provides a formidable problem where biomass resource utilization may need to be stretched to its maximum limit.

Although the availability of fertile land (88% of the total land), water from rainfall (120 cm to 345 cm per year) and rivers, and the possibilities of exploiting domestic natural gas are some of the advantages, they are not enough compared to the magnitude of the problems of a country with a very high population density and average income of US-Dollars 100 per person per year.

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2. BRIEF SURVEY OF LITERATURE AND THE SCOPE OF PRESENT WORK

Rural energy in Bangladesh has been discussed by several authors. The major contributions are made by the following studies:

(1) Bangladesh Energy Study (BES) (1978), commissioned by the Bangladesh Government with the help of other agencies, such as the UNDP, is most extensive. Although largely formulated for initiating projects concerning commercial energy such as natural gas, electricity planning, refineries, fertilizer plants etc., it devoted a chapter to non-commercial energy use because of its importance approaching it from the point of bio-mass availability.

(2) R. Tyers (1978) mainly deals with investment planning for agriculture, particularly in irrigation and fertilizers. He takes the BES study as the basis for non-commercial energy data and elaborates on the agriculture sector, and animate energy contributions.

(3) Briscoe (1979) has considered energy flows in the Uliper village, consisting of 42 families. He has specially stressed the social and political structures for transferring fuels among various social, economic and religious groups, and possible tensions emerging from such transfers.

(4) N. Islam's (1980) Nabagram Union study of 28 villages is elaborate and detailed, but the proximity of Nabagram Union to Sunderban forests may have an influence on wood-consumption, time spent in gathering fuels and use of fuels other than wood. This makes the Nabagram Union different compared to the rest of Bangladesh. It has high wood consumption but low consumption of agricultural waste, jute sticks and dung. However, his descriptions of homestead structures and existing and improved stoves lead one to a closer appreciation of reality.

(5) A comprehensive summary of the above is made by Manibog (1982), who also gives details on action programs to be carried out by the World Bank and others. All of the above studies are either region-specific or village-specific, or deal with household energy at the aggregate per capita level.

(6) Household energy consumption patterns and income distribution at the national level are discussed only recently in a paper by Kennes et al (1983) using the data of the household expenditure survey by the Bangladesh Bureau of Statistics (BBS). This study, which is also a part of the present exercise, analyses primary household energy data and assigns

them to nine income classes: seven in rural areas and two in the urban areas.

The present paper takes off from where the study by KPS (1983) left and re-examines some of the assumptions in a modeling framework where many of the interrelationships are more rigorously tied in. As can be seen later, this paper deals with many additional aspects which, on cross-checking with other data, has firmed up a considerable number of parameters. A critical analysis of data and relationships also leads to some policy implications, as will be shown later.

2.1. Simplification of the Model Due to Data Availability

The following aspects of the model described in Part I, which will be tackled later on in a more detailed exercise being carried out at CWFS, are not included in the present version which is meant for analysis of short term issues only.

a) Month index is altogether dropped in the computations. The model then is not suitable for looking into services provided by cattle whose peak requirements for ploughing are one of the major reasons for keeping it. When the model is run with month-wise details, in addition to the issue of mechanization vs. animal power it would also demonstrate periodic surpluses and shortage of fuels and their effects on fuel substitution.

b) Since the emphasis here is on studying fuel-fertilizer-fodder relationships, non-agriculture population is excluded. This could lead to a larger supply of bio-mass than perhaps there actually is.

c) Labor requirements are ignored partly because of abundant labor in Bangladesh.

d) Choices of lighting were not considered because in rural areas at present it is almost exclusively by oil (kerosene) lamps with a few exceptions.

It is hoped that these issues, when analyzed later, will give additional insights. In particular, when investment is also considered, the model would be suitable for analyzing medium term issues of dynamics of change in the system. Having made these simplifications in the model we proceed to discuss inputs and results in the subsequent sections.

3. INCOME GROUPS OF FARMERS AND HOUSEHOLD ENERGY CONSUMPTION

Since household energy is a major component of the rural energy system, some description of that sector is necessary in order to appreciate the purpose of this exercise and issues involved. Details are given elsewhere.

It is extremely important to distinguish different income groups whose behavior differ in terms of fertilizer use, energy use, and a number of other socio-economic aspects, such as family size, asset acquisition, etc. The large farmers also have more animals, more trees, and of course, more agricultural waste.

Table 1. Number of people and households per socio-economic group.

	People		Households			Income		
Socio-economic group	Number ('000)	%	Average size	Number ('000)	%	Income per cap. taka	Expenditure per cap. taka	Savings per cap. taka
a. Small farmers 0-1.5 acres	9,672	11.8	5.40	1,790	12.4	979	883	96
b. Medium farmersI 1.5-5.0 acres owner cultivation	10,917	13.4	6.65	1,642	11.3	1,171	1,022	149
c. Medium farmers II 1.5-5.0 acres owner cum tenant	10,035	12.3	6.65	1,509	10.4	1,445	1,200	245
d. Large farmers 5.0-7.5 acres	6,020	7.4	8.29	726	5.0	1,704	1,310	394
e. Very large farmers > 7.5 acres	6,065	7.4	10.29	590	4.1	2,773	1,631	942
f. Landless farm labourers	16,912	20.7	4.54	3,725	25.7	774	721	53
g. Non-agricultural rural	14,663	17.9	4.54	3,230	22.3	1,251	1,038	213
h. Urban informal	4,340	5.3	5.84	743	5.1	1,099	1,007	92
i. Urban formal	3,143	3.8	5.84	538	3.7	2,143	1,622	521
Total	81,765	100.0	5.64	14,497	100.0	-	-	-
Total agriculture (a+b+c+d+e+f)	59,619	72.8	5.97	9,986	68.9	-	-	-

Source: H. Stolwijk (1981) and W. Kennes (1982).

Bangladesh Bureau of Statistics (BBS)(1982).

A household expenditure survey (HES) was carried out by the Bangladesh Bureau of Statistics using 16,475 households as samples across nine different income classes. These are converted into land-holding classes so as to make its relationship with agricultural assets and activities explicit (H. Stolwijk, 1981; W. Kennes, 1982). The distribution across classes is given in Table 1. As 90% of the population lives in the rural areas, seven income groups of rural population and only two income groups of urban population are considered. The urban-formal group includes people in government, industry, commercial and service sectors. The distribution of different income groups is given in Figure 1.

3.1. Some Problems with the Energy Data

More than 90% of the rural household energy is supplied by non-commercial energy sources. It is difficult to convert a wide variety of these fuels with varying degree of moisture contents, heat values and volatile matter to the same units using one heat value per fuel, particularly across several income classes. The landless may, for example, gather twigs and branches whose value in money terms and energy terms are difficult to quantify. Thus, using an average figure of 15 GJ/ton of wood may give a high estimate for energy use by income classes which use twigs, and an underestimate for high income classes which may use good quality wood having 18 GJ/ton.

The same type of bias is expected to occur in value terms because of the differences in the quality of the two products. For example, gathered fuels, whose quantities and quality standards are doubtful, are converted into taka presumably using prevalent prices for each of them, which may again differ with region, season, quality and supply availability. There is also ambiguity about converting time spent on gathering fuels into money terms so as to account this activity in the income of the households. Thus, "budget share" for energy expenditure may have several information and assumptions built into them. Notwithstanding these difficulties, the following conclusions emerge:

3.2. Budget Shares

On the average, nearly 70% of the household expenditure is on food items. The actual magnitude varies from 75% for the rural poor to 65% for the rural rich. The urban-formal class also spends 60% of the expenditure on food. A third of the remaining 30% of the budget is allocated to household energy leaving the rest 18% to 23% of the total budget on clothing, housing and other

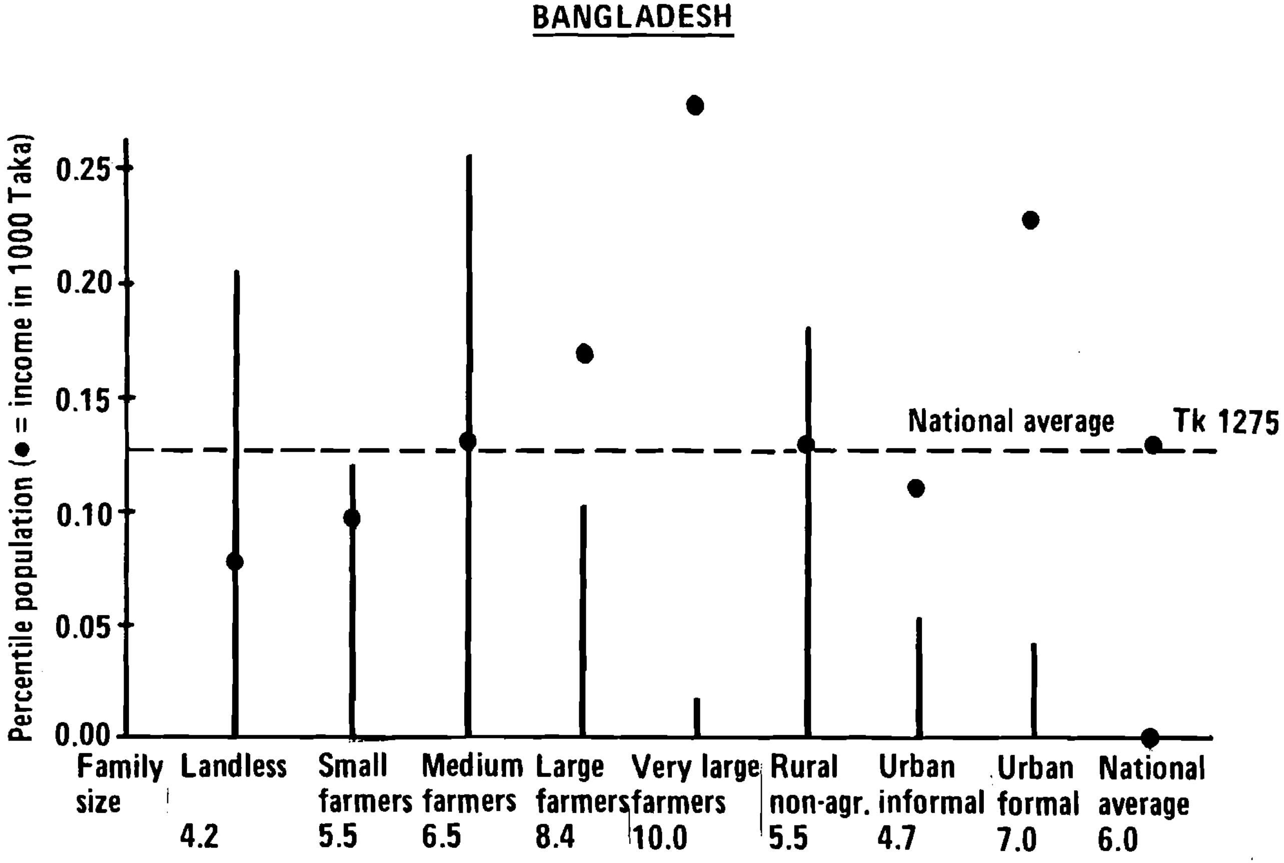

Figure 1. Distribution of different income groups and their average income during the years 1976-1977.

necessities. The budget shares allocated for household energy expenditure vary from 6.9% for the urban-formal class to 10.7% for the landless. The urban-formal class not only has a high total expenditure but access to more efficient forms of commercial energy, such as kerosene and natural gas (available to households in Dhaka), which are cheaper if considered in useful energy terms. The average national budget share for energy is 8.7% of the household expenditure. For the lowest to the highest income groups, the energy expenditure ranges from 77 taka (TK) to 181 taka* per capita, and amounts to 7.22% of the average per capita income. (The national ratio for expenditure to income is 82%.)

The variations across income classes are small compared to some of the other developing countries. However, the mix of energy forms differs considerably from income class to income class. Even these small differences among income classes reduce when one considers useful energy consumption, as we shall see later.

3.3. Percentage Shares of Various Fuels

3.3.1. Value terms.

Since wood lends itself more easily to commercial transactions is more profitable to transport than other traditional forms of energy, it is sold to rural non-agriculture classes and to the urban areas.

Very large farmers spend 70% of energy expenditure for different types of agricultural waste and dung, and only 17% for wood and 10% for kerosene, respectively. Due to large holdings, they generate excess agricultural waste, straws and jute sticks to burn and therefore obtain 11%, 27% and 17% energy respectively from these sources. The maximum contribution from jute sticks is obtained by this class. This energy expenditure pattern is graphically shown in Figure 2.

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*15 taka = 1 US dollar; the help of Jan Morovic in processing household energy data is gratefully acknowledged.

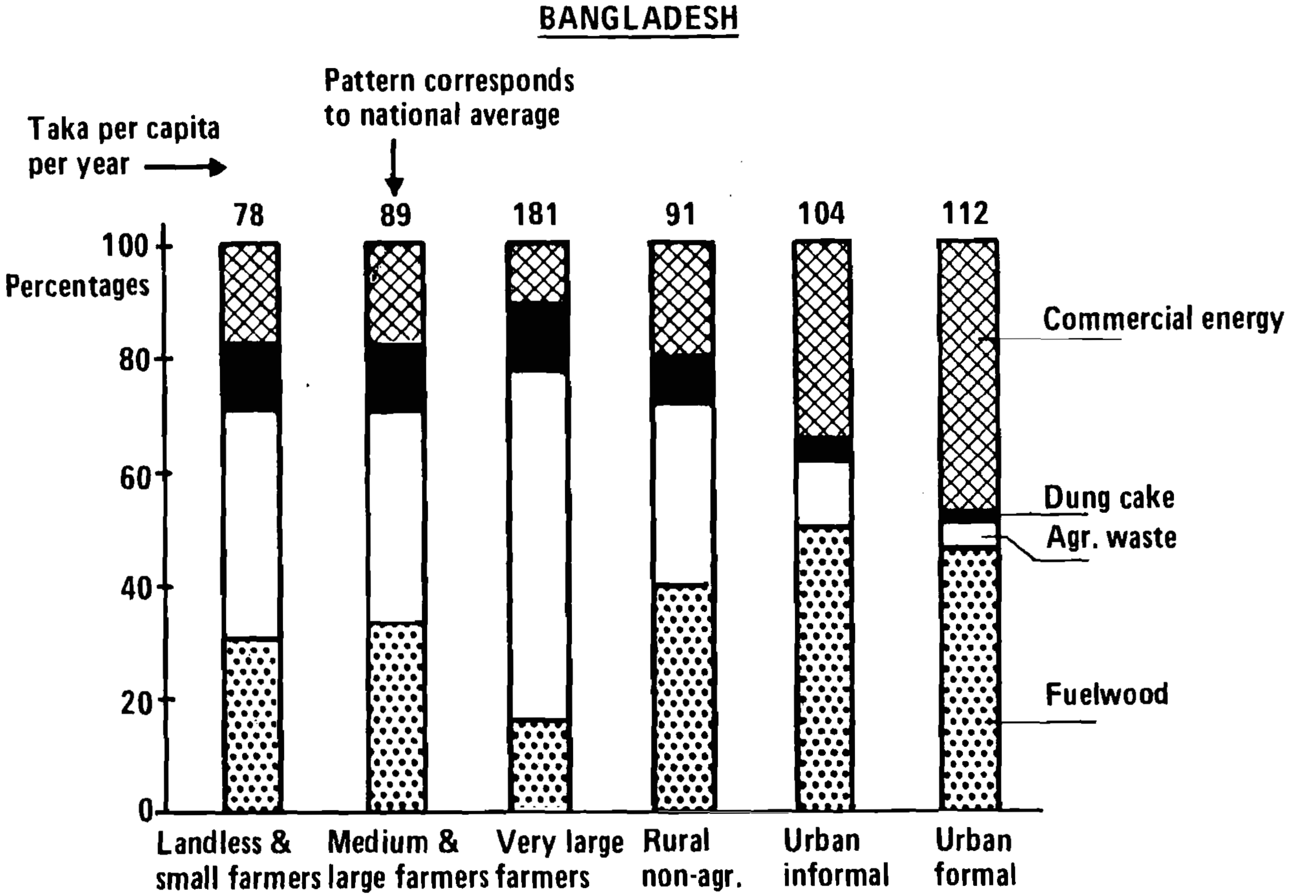

Figure 2. Percentage distribution of expenditure made on various fuels in 1976-1977 in value terms.

3.3.2. Primary energy terms

Converting the quantity units into energy terms using Table 2, one finds that the national average consumption of 5 GJ per capita consists of 36% wood, 18% dung, 10% straw, 27% agricultural waste (essentially from rice), 3.8% from jute sticks, 4% from kerosene, and 1.6% from electricity. However, there is a considerable difference between rural and urban energy consumption in amounts and patterns. The energy consumption pattern is shown in Figure 3.

Table 2. Supply and demand balance at national level for energy resources.

	National use in million t[a] from BBS	GJ per quantity[a]	Assumed efficiency	National consumption TKJ (10^{12}KJ) (primary)	Estimate by BES TKJ
Fuel wood[1]	9.88	15.0	0.12	148.0	45.4
Straw	3.26	12.6	0.08	40.9	38.0
Dung cake[2]	5.22	13.8	0.10	72.2	52.7
Agr.waste	8.71	12.6	0.08	109.5	50.6
Jute stick	0.87	18.0	0.15	15.5	12.7
Bagasse	0.40	7.4	0.10	3.3	11.6
Coal[3]	0.088	24.0	0.15	2.1	-
Kerosene[3] (1000 lit.)	390	35.0	0.35	13.6	n.r.
Electricity[3] (10^6 kWh)	189	10.5	0.80	2.0	n.r.
Gas[3] (MCF)	7700	9093	0.65	7.6	n.r.

[a] Obtained by multiplying weighted per capita average of BBS with the national population (81.76 million in 1976-1977). Quantities are in tons unless mentioned otherwise. BES data is for 1973-1974 and is derived from supply considerations.

[1] BES data indicates fuelwood 7.4, twigs and leaves 19.0, and other fuels 19.0 MGJ.

[2] Collection coefficient of 50% is assumed.

[3] Consumption data from BBS survey for kerosene, electricity and gas consumption are very different from related data available from the corresponding ministries of supply. Since the per capita use is small (less than a few percent), multiplying with 81.8 million could lead to major inaccuracies in such small consumption. Therefore, the Government data on supply are quoted, i.e., 390,000 litres of kerosene, 189,000 kWh electricity, 7700 MCF natural gas, instead of BBS consumption data.

Useful energy is derived by multiplying the primary energy with the efficiencies. Table 2 gives the assumed average heat contents and the efficiencies for each type of fuel. For cooking and other uses, using these

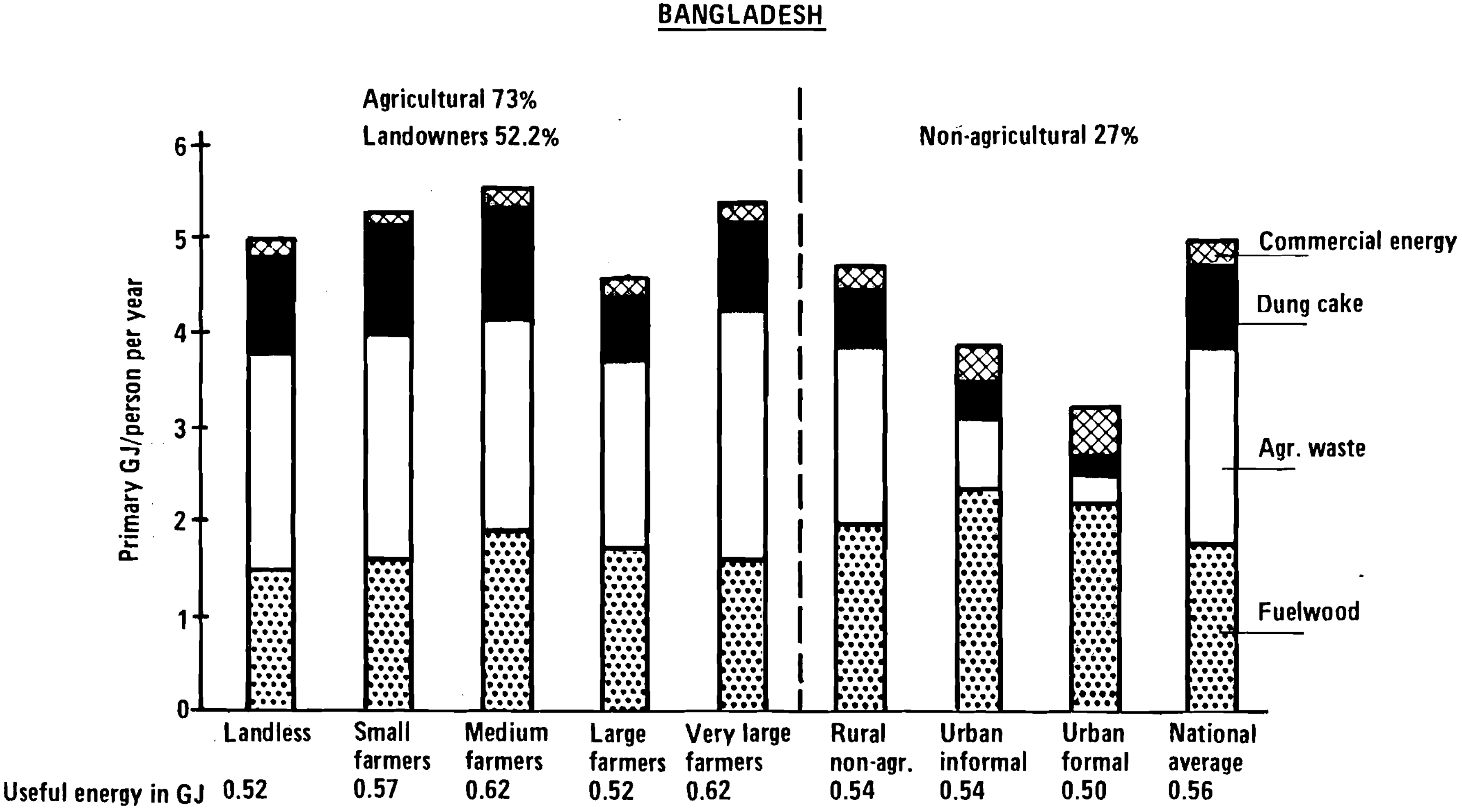

Figure 3. Household use of primary energy by different income classes, 1976-1977.

numbers, one finds that the useful energy consumption indicated for each income class in Figure 3 varies much less for different income classes than the primary energy consumption. They all fall in the narrow range of 0.52 GJ to 0.62 GJ per person. The anomaly discussed earlier, concerning much lower urban energy consumption than rural energy consumption, is resolved in this way.

4. CROP RESIDUE PRODUCTION

Rice, wheat and jute account for nearly 87% of the harvested area and revenues. In practice, there are two varieties of wheat and seven varieties of rice. Crop-residues for improved varieties is less than half of the traditional varieties. For example, grain to crop residue ratio is 1:1, 1:3.3 and 1:4.5 for improved, traditional aman and deepwater varieties, respectively. However, for computational purposes, variety differences for each crop are ignored. All crop residues are added up in the beginning of the calculations and separate uses for jute sticks, rice hulls, etc. are not considered. Nearly 80% of the cultivated land was under rice.

Unfortunately, the data for crop-wise fertilizer application (for rice and wheat separately) are available only for some farms but not at national level. Therefore crop-wise differences in fertilizer application are not considered. Related data is given in Table 3.

5. LIVESTOCK SECTOR

The ownership of animals according to income groups are given by Stolwijk (1982) and are reorganized by us in terms of working and non-working animals as shown in Tables 4 and 5.

The working and non-working animals had to be separated because of higher calorie intake of working animals. In the present study animal calorie and protein requirements were taken to be 2.6 Mkcal and 80 kg of protein respectively. for non-working including calves, and 3.8 Mkcal and 80 kg of protein for working animal. A kg of feed from rice straws contain 1600 kcal and 35 g of protein. It is assumed that one fourth of the feed will come from the grassland including fallow land. The livestock related data adapted for the model are given in Table 6.

Table 3. Crop-related data for Bangladesh 1976-77.

Indicators	Units	Wheat	Milled Rice	Jute
a) Crop residue per ton of crop incl. straws, husk and all by-products	ton	2.5	2.5	3.5
b) Yield by income class j	ton/ha			
small		1.48	1.92	1.32
medium (owner)		1.50	1.77	1.32
medium (tenant)		1.51	1.73	1.32
large		1.52	1.65	1.32
very large		1.57	1.60	1.32
c) Land area by j	1000ha			
small		15.54	736.39	54.35
medium I		36.79	2170.08	151.23
medium II		36.45	2093.68	145.85
large		45.97	2906.39	191.98
very large		26.22	1975.74	105.46
TOTAL		160.06	9882.33	648.87
d) Price per ton	Taka	2048	1699	2690

Calorific value of crop residue as feed is taken as 1.6Mkcal/ton with protein content 35kg/ton.

Table 4. Number of cattle per socio-economic group ('000 animals).

Socio-economic group	< 1	Age 1 - 3	> 3	Total
Landless labourers	298	295	753	1,346
Small farmers	409	415	1,713	2,537
Medium farmers, tenants	516	449	2,395	3,360
Medium farmers, owners	908	791	4,216	5,915
Large farmers	698	685	3,449	4,832
Very large farmers	353	370	1,796	2,519
Total	3,182	3,005	14,322	20,509

Table 5. Number of working animals ('000 animals).

	Cattle			Total male cattle*
Socio-economic group	Male	Female	Buffaloes	driving power equivalent
Landless labourers	211	64	8	259
Small farmers	771	530	10	1,056
Medium farmers, tenants	1,269	656	23	1,643
Medium farmers, owners	2,234	1,153	42	2,895
Large farmers	2,035	464	104	2,475
Very large farmers	1,096	447	190	1,699
Total	7,616	3,315	376	10,027

*1/2 working buffalo ~ 1 working male cattle ~ 2 working female cattle.

Source: Stolwijk, H. (1983).

Table 6. Livestock-related data 1976-77, adapted to the model.

Indicators	Units	Non-Working Cattle	Working cattle (incl.buffaloes)*
a) Ownership			
by income class	10^3A		
small		1236	1056
medium I		1435	1643
medium II		2528	2895
large		2333	2475
very large		976	1699
landless		1071	259
TOTAL		9579	10027
b) Calorie intake per animal per year	Mkcal/A	2.6	3.8
c) Percent obtained by grazing	%	30	30
d) Dung output per animal per year	t/A	0.65	0.95
e) Fraction of dung collected	t/t	0.8	0.5

*1 cow = 1/2 bullock; 1 bullock = 1/2 buffalo (for ploughing purposes).

6. FERTILIZER SECTOR

In Tables 7 and 8, chemical fertilizer consumption by each income class is given in terms of the three nutrients used per hectare. While the magnitude of fertilizer use was obtained from BBS it was assumed that all income groups use the N, P, and K in the same proportions. i.e., 68.6: 25.4: 6.0 In some of the earlier runs, it was assumed that equal amount (i.e. 50% of the total) in addition will come from organic fertilizers, i.e. manure from dung and burning crop residues. However, as we shall see later, this is an over-estimation and perhaps less than 30% comes from organic fertilizers.

7. RESULTS OF THE MODEL

Food-fodder-fuel-fertilizer relationships in agricultural Bangladesh

The resource system of Bangladesh is extremely constrained and precariously balanced. These features are captured in the linear programming type model developed here, where some choices are made partly on price considerations, i.e., relative prices of fodder, fuel and fertilizer and partly on matching assets (livestock, land), energy supply therefrom and the energy requirements. In other words, due to the way the objective function is specified so as to minimize cash purchases, small households do not go out to sell a few kilograms of dung or straws--which would be the case if the objective function would be specified with implicit prices of the by-products--but puts priority on self-sufficiency and uses own resources first prior to purchasing commercial energy, inorganic fertilizers or commercial feed. In fact, small changes in relative prices do not alter the solution drastically because of a variety of biomass allocation mechanisms taking priority. This is explained in detail in the following parts of this paper.

Due to uncertainties in the data a number of variations were made to test the model, to examine consistency and to probe sensitivities. A "base run" is selected for the purpose of providing a revenue system that describes, in our view, the reality as close as possible. Nearly 50 runs are made for the sensitivity analysis and to probe the ranges of uncertainties in the parameters.

Table 7. Total consumption in metric (10^3) tons.

	Small farm	Medium farm tenants	Medium farm owners	Large farmers	Very large farmers	Total
Urea	27.5	75.2	78.9	102.2	75.2	359.0
TSP	9.8	26.7	28.0	36.3	26.8	127.6
MP	1.7	4.8	5.0	6.5	4.7	22.7
NP	0.3	0.9	0.9	1.2	0.8	4.1
NPK	0.5	1.3	1.3	1.7	1.3	6.1
SP	0.1	0.3	0.3	0.4	0.3	1.4
Total	39.9	109.2	114.4	148.3	109.1	520.9

Source: Stolwijk, H. (1983).

Urea: 46% N
TSP: 46% P_2O_5
MP: 60% K_2O
NP: 42% P_2O_5
NPK: 15-15-15
SP: 18% P_2O_2

Average prices per kg nutrient:

1 kg N	T 3.49
1 kg P_2O_5	T 2.80
1 kg K_2O	T 1.79

Table 8. Nutrients from inorganic fertilizers in kg/ha.

	N	P	K	Total
Small	8.243	3.058	0.706	12.007
Medium I	7.612	2.823	0.671	11.106
Medium II	8.277	3.063	0.723	12.063
Large	10.899	4.040	0.957	15.896
Very Large	4.895	1.817	0.423	7.155
Total	7.561	2.804	0.661	11.026
%	68.576	25.429	5.993	100%

Adapted to the model from the original source given above.

7.1. How Does the Present System Behave?

7.1.1. Selection of the base run for 1976

A number of runs had to be made to reproduce the existing rural energy system which in present case is characterized by certain energy use and inorganic fertilizer use that is already reported for the year 19761. The ranges of parameters had to be tried to get a reasonable run characterizing the present energy system of Bangladesh. In the base case for 1976, *some* of the already known features, such as amount of inorganic fertilizers used, commercial energy purchased, wood supplied, etc., was held fixed as it is already known. However, this was not the case for the policy runs where the model was allowed to make optimal choices. These changes are as follows.

(a) Increase of "wood" supply from 6 Mt to 10 Mt (includes branches and twigs and to some extent leaves)

(b) Increase in cooking efficiencies (which also leads to additional resources as less resources are required for obtaining the given demand of useful energy)

(c) Increase in dung collection coefficients for non-working animals to 90% from 80% and for working animals 50% to 80%

(d) Reduction in straw consumption from 1.7 tons per animal to 1 ton per animal. (The latter implies that either large quantities of feed come from pastures and grains or that cattle are starved to a considerable extent.)

Since there are a number of uncertainties in the actual data of each of these parameters described above, these scenarios gave insights into "bounds of the system". It is interesting to see that none of these "improvements" led to additional unused organic materials in the system. They only reduced the purchased or deficit fertilizer, fuel and fodder. In other words, there was no case when supply of biomass was in excess compared to the needs.

Some selected runs are reported fully in Table 9 and are described below.

Run 1 The base run is selected as the one which represents the 1976-77 situation as closely as possible. It is characterized by 10 mt of total wood supply for cooking, 13Mt of collected dung supply, 53 kg/ha of total fertilizer application ratio and fuel efficiencies as given in Table 2. The fuel:fertilizer ratio for the dung works out to be 50:50.

Table 9. Base Run (corresponding to 1976-77) and Variations of Assumptions.

Fuel	Base Run[a] 1		Wood Availability 8 mt 2		Dung Availability 18 mt 3		Fertilizer Rate Reduced 33 kg/ha 4	
(Per capita energy for cooking)								
Crop residual (kg)		140		165		140		140
Animal dung (kg)		105		129		105		105
Fuelwood 1 (kg)[b]		64		64		64		64
Fuelwood 2 (kg)		97		64		97		97
Commercial energy:[c]								
Kerosene (l)		0		0		0		0
Electricity (kWh)		0		0		0		0
Organic (dung + crop. res. + biogas)[d]								
N kg/ha (%)	6.6	20	5.2	16	11.6	35	6.6	24
P kg/ha (%)	3.9	31	3.0	24	6.8	55	3.9	35
K kg/ha (%)	7.6	99	5.9	77	13.5	100	7.53	62
Inorganic								
N kg/ha (%)	26.8	80	28.2	84	21.8	65	21.4	76
P kg/ha (%)	8.5	69	9.4	76	5.6	95	7.1	65
K kg/ha (%)	.0	1	1.7	23	0	0	4.7	38
Dung total (1000 t)		13197		13196		18475		13197
Fertilizer (%)		50		39		64		50
Fuel (%)		50		61		36		50
Crop residual (1000 t)		45723		45723		45723		45723
Fertilizer (%)		4		4		4		4
Fuel (%)		19		23		19		19
Fodder (%)		61		57		61		61
Other (%)		16		16		16		16

[a] Base run is characterized by 1976 data + 10 mt wood, 13 mt dung, 53 kg/ha total fertilizers. The rest of the runs are like base run except for the change that is shown.

[b] These two categories to be viewed together. The distinction between the two is not considered due to data limitation in all of these and subsequent runs.

[c] Since this version of the model excludes energy for lighting, kerosene and electricity uses are negligible in the base run.

[d] Percent share of organic fertilizers for a particular organic nutrient is shown. The remainder comes from inorganic sources.

Run 2 Same as base run, except 8Mt of total "wood" supply instead of 10Mt. Due to reduction of wood supply dung utilization for fuel increases and fuel:fertilizer ratio of dung reduces to 61:39.

Run 3 Dung output per animal is taken to be 0.91 t for non-working and 1.33 t for working animals, giving on the average collected dung of 0.9 t per animal as assumed by most in the literature but is probably unrealistic considering the age distribution of cattle and fodder availability in Bangladesh. Interestingly, the additional dung put into the system does not get burnt, but is allocated to fertilizer, giving the 36:64 fuel:fertilizer ratio assumed in the literature.

Run 4 This run is similar to the base run but has somewhat reduced (33kg/ha instead of 53kg/ha) fertilizer application rates which reproduces actual purchase of chemical fertilizers reported for 1976-77 more closely than the base run. This should have been characterized as the base run. This, however, has little effect on the energy picture and, therefore, the base run was not changed for the sake of convenience. It is interesting to see that no changes in the energy scene can be seen in the above runs, implying that fodder and energy needs are met first and then adjustments are made in the fertilizer sector. Thus, all the variations given above use about 6 million t of dung for fuel, first and then use varying amounts of dung for fertilizer depending upon the availability.

Seen from another angle, the model is used to predict the ranges of unknowns in the system. For example, the estimate in the literature for fuelwood use (including twigs, leaves and branches) in Bangladesh range from 4 million tons to 20 million tons per year (BES). A special inquiry carried out by FAO (Douglas 1981) puts these estimates around 6 million tons. The results of the model suggest that the wood supply has to be between 8Mt to 10Mt at least to meet other constraints that one has in the system. The fuel efficiencies of non-commercial fuels also could not be as low as 5% as presumed by some but range around 10%. (However, this could be best settled by assessments in the laboratory of a few representative cooking stoves and fuels. Islam's experiments suggest 10% efficiencies).

Thus the model helps in fixing the uncertain parameters in that there is no alternative way to meet the quoted demand by HES except with wood ranging from 8 Mt to 10 Mt of fuel wood, fuel efficiencies of the order of 10%, fodder availability of about 1.4 to 1.7 t per animal and dung collection of about 0.7 tons per animal. Tyers assumes 0.5 tons per animal which is too low. Manibog (1982) and many others including BES, on the other hand assume only 35% of use of dung for fuel but the present study puts it at much higher level - at around 50% on the average and going up to 90% for small farmers.* To provide 0.7 t of dung, the straw consumption has to be at least 1.6 t (40% to 50% of fodder is converted into dung) collection efficiency of dung has to range to 90%. These happen to be the values taken in the model. Another interesting feature of the results is that the 300 kcal of utilizable energy (at 10% efficiency) that is in a kg of dung is 4 to 5 times more valuable at the prevailing prices of fuel and fertilizers in most developing countries than the 10 g of N, 6g of P and 12g of K that it contains. These are also the conclusions of the recent study by Aggarwal and Singh (1984), who have done a cost-benefit analysis for a state in India. Thus, if the farmers use dung for manure at all it is due to one or more reasons stated below:

(i) They have other better and preferred fuels (such as commercial energy or wood) available and they do not need to use dung for fuel on economic grounds.

(ii) The value of manure in terms of nutrients is a minor aspect compared to the improvements brought about in soil characteristics by providing humus and organic matter to hold the plants.

(iii) Some additional possibilities (but unlikely) are that they are simply unaware of economic advantages of burning dung compared to using it as manure.

(iv) More likely reasons could be *unavailability* of chemical fertilizers and commercial fuels in the rural areas at the quoted prices and the relative needs for these in different seasons.

(v) In addition to the economic advantage for burning dung, additional reasons could be that both the supply of dung and need for fuel are continuous (daily) functions of time rather than peaked during a season, and minimizes the effort of stocking. It is not likely that a woman will go several

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*Interestingly, this often quoted figure of 35% use of dung for fuel purposes is used by many studies of Bangladesh and several other countries which has origin in a reference for India. The authors had serious reservations about this number. These doubts are confirmed by the model runs. It may be appropriate to incorporate this point in future rural energy surveys to get a clearer picture.

kilometers to collect wood when she could use the dung from her backyard. Thus, its use for fertilizers--which is a seasonal need--could have low priority during off-season. During monsoon, when it is difficult to dry dung for fuel, it is better to use it as manure in the fields.

The last reason especially applies to Bangladesh and resource scarce regions of developing countries where fuel scarcities are severe. A pilot sample survey needs to be carried out to ask the questions suggested above, test some additional hypotheses and ascertain who uses dung for manure and why.

In particular, the use of high average norm of 0.9t to 1t of dung per animal leads to for over estimation of dung up to 20 million tons. But when one considers that a third of the animals are calves of the age less than 3 years and uses the norm of 0.7t, then the total availability decreases to 13Mt. When the supply was arbitrarily increased to 20Mt in one run, the dung is used for burning and the rest is used for other purposes, there still remained 6Mt as in the case of 13Mt. Thus, 6Mt is 35% of 20Mt but 50% of the 13Mt. This then explains why the present study differs from others.

7.2. Would all the Farmers Accept HYV? Under What Conditions?

It is argued by some that High Yielding Varieties (HYV) are not acceptable by the farmers because of the small straw output per ton of grain that HYV give compared to the traditional varieties (1:1 rather rather than 2:1 or 3:1).* Therefore, the model runs were made to find out biomass implications of measures of introducing HYV.

The HYV are specifically bred to give more grain than the straw. However HYV require much more fertilizer compared to the traditional varieties. Assuming 1 kg of fertilizer gives 10 additional kg grains, 100% increase in fertilizer levels in Bangladesh (from 33 kg to 66 kg) could lead to increase from 1.5 tons of paddy per hectare to nearly 2 tons per ha., i.e., 30% increase. 200% increase in fertilizers i.e., 100 kg per ha leads to the average yields of 2.5 t/ha for paddy and wheat and 1.7 t/ha for Jute. Thus, two levels of fertilizer application were considered with two levels of prices, base run prices, i.e. actual prices of (1976) and "increased" prices. The crop-residue coefficients for traditional

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*Manibog (1982) mentions that fuel value of jute is so valuable that fibre is considered by-product. Tyers (1978) finds that on increasing energy prices rice growing the small farmers switch to jute growing. The present model does not go into crop allocation and assumes it to be fixed.

and HYV scenarios were given in Table 3. The results are discussed below and are summarized in Table 10. There are also other factors which increase yield, such as irrigation, soil improvements, etc., but only yield increases due to fertilizers are considered.

As we are concerned only with policy scenarios, viz. how would farmers of different income groups respond to the introduction of HYV and under what conditions, it is assumed, for the sake of simplicity, that *all* the farmers switched to HYV, keeping other conditions of 1976 for runs (2) and (7) constant and for runs (8) and (9). Population in 1983 is used, keeping all the state variables, except fertilizers and yields constant. Therefore, the results are dramatic. Of course in real life, the farmers would switch gradually but this run is made to assess the policy implications of introducing HYV on farmers of different income groups. It is interesting to see that 30% increase yield due to HYV reduces availability of crop residues from 45.5 Mt to 35.5 Mt. But when the fertilizers levels are increased threefold, leading to a 60% yield increase, then again the availability of crop residues increases sufficiently such that the original situation is approximately restored. In fact, runs carried out without HYV show that in the short term, the farmers are better off without HYV as far as fuel and fodder are concerned.

The most hurt are small farmers whose fodder availability per animal is reduced to half in the second case and does not retrieve itself even in the third case. Medium level farmers' fodder availability is reduced by 15% in the third case. Large farmers have enough fodder in both cases, but their fuel use of crop residues decreases in the second case.

7.3. What Could Happen When Population Increases?

The population of Bangladesh is assumed to have increased at 3% annually until the year for which the base runs of the model is made. Population increases of 20% and 40% over 1976-77 figures are considered as two cases. How do the allocation patterns change in such a situation? It is assumed that per capita useful energy for cooking, which is the lowest in the world, does not change. The population increase of 20% and 40% respectively is assumed to take place evenly in all classes and the questions related to diseconomies of scale for subdivided farms of smaller units are not considered. To feed this population somewhat better than today, 60% increase in yields and 3 times higher fertilizer application rates is assumed, rationale for which is discussed

Table 10. A Comparison of the Base Run with HYV Scenarios.

Fuel	Base Run 1		Double Fertilizer 30% Higher Yields with HYV 5		Triple Fertilizer 60% Higher Yields with HYV 6		Double Fertilizers 30% Higher Yields without HYV with 20% more Population 7		Triple Fertilizers 60% Higher Yields with HYV with 20 more Population 8	
(Per capita energy for cooking)										
Crop residues (kg)		140		68		130		190		164
Animal dung (kg)		105		175		115		94		120
Fuelwood 1 (kg)		64		64		64		53		53
Fuelwood 2 (kg)		97		97		97		81		81
Commercial energy:										
Kerosene (lit.)		0		0		0		0		0
Electricity (kWh)		0		0		0		0		0
Organic (dung + crop. res. + biogas)										
N in kg/ha (%)	6.6	20	2.0	3	5.9	6	7.4	11	4.0	4
P in kg/ha (%)	3.8	31	1.2	5	3.5	9	4.0	16	2.4	6
K in kg/ha (%)	7.6	99	2.5	35	6.9	63	7.4	76	4.8	44
Inorganic										
N in kg/ha (%)	26.8	80	64.8	97	94.4	94	59.5	89	96.2	96
P in kg/ha (%)	8.5	69	23.5	95	33.6	91	20.8	84	34.7	94
K in kg/ha (%)	.0	1	4.6	65	4.1	37	2.3	24	6.2	56
Dung total (1000 t)		13197		13197		13197		13197		13197
Fertilizer (%)		50		47		46		47		32
Fuel (%)		50		53		54		53		68
Crop residues (1000 t)		45723		35552		43756		59440		43756
Fertilizer (%)		4		0		3		12		1
Fuel (%)		19		12		18		24		28
Fodder (%)		61		67		62		49		51
Other (%)		16		21		17		15		20

See footnotes for Table 9.

in the earlier scenario. No increase in livestock is assumed because they have been approaching a stable level for the last few years. (Though this is not true of goats, which are not in this energy model because they do not work.) The results of the two scenarios are summarized in Table 11.

It can be seen that the continuation of the 1976-77 pattern could almost be managed on the average in 1983 with some modifications, of course, and with considerable hardships to the landless and small farmers. The situation in 1990 is especially alarming. In spite of large inputs of purchased commercial energy for cooking and significant addition of chemical fertilizers (increase to 60 kg/ha), fodder of the order of 0.8t per animal would be required so as to replace the agricultural residues which get burned in the households. By this time not only the landless and small farmers but even the middle farmers are vulnerable, not only in fodder requirements, but also in energy requirements. This is because with the same amount of land and animals, they cannot support 40% higher population. However, large and very large farmers manage to balance all their requirements even in 1990.

Although in Bangladesh cooking with natural gas based electricity appears to be more desirable than with kerosene, which has to be imported and is highly taxed, this option is not put into the model as we are concerned with rural areas where natural gas cannot be transported for a few consumers.

Biogas, charcoal and ethanol production programs may have relevance in special farms, but their contributions to the national energy scene would not be significant.

Even to keep 10 million tons of fuelwood supply (for cooking only) going in the future may require afforestation programs, because as shown by Douglas (1982) the present supply of about 10 Mt already comes from deforestation and is more than the natural regeneration limits.

8. FOOD-FODDER-FUEL-FERTILIZER RELATIONSHIPS IN AGRICULTURAL BANGLADESH: Highlights and Implications

Food-fodder-fuel-fertilizer relationships are complex in case of resource constrained Bangladesh where high population density reduces the per capita availability of biomass to a great extent. Moreover, due to the low purchasing power long term solutions, which may be desirable, are limited.

Table 11. Comparison of Base Run with High Population Scenarios in Future.

Fuel	Base Run 1		30% Higher Yields without HYV + 20% more Popultion 7		60% Higher Yields + 20% more Population 8		60% Higher Yields with HYV + 40% more Population 9		60% Higher Yields + 40% more Population + higher cooking Efficiency 10	
Corresponding year	1976		1983		1983		1990		1990	
(Per capita energy for cooking)										
Crop residual (kg)	140		190		164		188		78.6	
Animal dung (kg)	105		94		120		113		71.3	
Fuelwood 1 (kg)	64		53		53		46		45.6	
Fuelwood 2 (kg)	97		81		81		69		69.5	
Commercial energy:										
Kerosene (l)	0		0		0		0.58		0	
Electricity (kWh)	0		0		0		2.28		2.28	
Organic (dung + crop. res. + biogas)										
N in kg/ha (%)	6.6	20	7.4	11	4	4	3.1	3	6.7	7
P in kg/ha (%)	3.9	31	4	16	2.4	6	1.9	5	4	11
K in kg/ha (%)	7.6	99	7.4	76	4.8	44	3.7	35	7.9	72
Inorganic										
N in kg/ha (%)	26.8	80	59.5	89	96.2	96	97.2	97	93.5	93
P in kg/ha (%)	8.5	69	20.8	84	34.7	94	35.3	95	33.2	89
K in kg/ha (%)	.0	1	2.3	24	6.2	56	7	65	3.1	28
Dung total (1000 t)	13197		13197		13197		13197		13197	
Fertilizer (%)	50		47		32		25		53	
Fuel (%)	50		53		68		75		47	
Crop residues (1000 t)	45723		59440		43756		43756		43756	
Fertilizer (%)	4		12		1		0		2	
Fuel (%)	19		24		28		38		16	
Fodder (%)	61		49		51		39		59	
Other (%)	16		15		20		23		23	

The purpose of this study is threefold:

(a) verification of existing data and identification of crucial parameters

(b) understanding of dynamics of interrelationships for different income groups

(c) insights into future developments.

We take each purpose in turn.

8.1. Dynamics of the Fodder-Fuel-Fertilizer Interrelationships

These are studied under varying conditions such as changes in prices, biomass availability, efficiency improvements in utilization etc. However, prior to that considerable time had to be spent on data analysis. In doing so, some estimates which are somewhat ambiguous so far in the literature are firmed up. These ranges are, for example, 8Mt to 10Mt wood supply, 10% fuel efficiencies for cooking, dung use for fuel:fertilizer 50:50, straw consumption per cattle 1.4 to 1.7t/animal with dung output of about 0.7t/animal.

It seems that nearly 3000 kilocalories that is contained in a kg of dung which could be burnt at 10% efficiency is more valuable than fertilizer contents that vis 0.01 kg of nitrogen, 0.006 kg of P and 0.012 kg of K. In fact if nutrients are the only criteria for using manure -- and not the humus and improvements of soil quality -- then it would take 4 to 5 time increase in fertilizer prices before the small farmers would switch from burning it to using it for fertilizers. In other words, the dung will be used as manure only by those who either due to their income or fuel abundance have other preferred fuels, but those who do not have alternative fuels, would choose to burn dung for fuel rather than use it as fertilizers.

8.2. Insights into Income Groups

Our results show that subsistence level households end up burning dung and sometimes straws. The reason for this is twofold: There is not enough biomass production available to the landless and small farmers to take care of need for fodder, fuel, and fertilizers of the farmers who have less than one ha of land and one or two animals. In the case of straws, the added use of it is to feed the animals, which is also preferred use over the use of crop-residues for fertilizers.

While changing to HYV for 20% additional yield or also when fuel wood availability is reduced from 10Mt to 8Mt landless and small farmer run into fodder deficits. They burn almost all their dung for fuel in many of the scenarios. More arguments for this are given previously in the base run. When population increases by 40%, even medium farmers are as vulnerable for fodder deficits.

The large and very large farmers of the villages also use crop residues for fuel, but in their case, even after meeting the cooking requirements, which is small in comparison with the bio-mass supply, there is enough available to feed the animals and for fertilizers. They use all their dung as manure and are not vulnerable even in 1990 when a 40% increase in population reduces their per capita land and animals.

8.3. Insights into Future Developments, and Strategies

(a) It is clear that most of the additional fertilizer required for the yield necessary to feed future population would have to come from inorganic fertilizers with the possible exception of potassium fertilizers.

(b) If High Yielding Varieties (HYV) are to be promoted, it would require a simultaneous support program for fodder for the animals, especially for the small farmers because they give 40% less crop residues. Additional fodder would be necessary till the time when the fertilizer doses become sufficiently high so that the high yields compensate for the losses (due to reduced crop residues per ton of yield).

(c) When in 1990, population would increase by 40% over its 1976 figure of 82 millions, additional fodder provisions of about 50%, (for the same number of animals as in 1976) large purchases of commercial energy and high inputs (100 kg/ha) of fertilizers may be necessary. Almost all the additional fertilizer inputs, except potassium, would have to come from inorganic fertilizers. Improvements in cooking efficiencies and even cooking with natural gas based electricity - which turns out to be cheaper than imported kerosene - need to be promoted.

An even more comprehensive exercise for obtaining better insights into the role of animal power vs. mechanization, monthwise shortages of fuels, the role of energy conversion technologies such as bio-gas plants, charcoal kilns, alcohol distilleries etc. is underway. The conditions for applicability to other countries are discussed at the end of Part I. Finally, it should be stressed that the issues discussed here are relevant for most low- and middle-income developing countries including many provinces of China and India and concern nearly 2 billion people.

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