# MODELING ENERGY AND AGRICULTURE INTERACTIONS: AN APPLICATION TO BANGLADESH

Jyoti K. Parikh and Gerhard Krömer
*Food and Agriculture Program, International Institute for Applied Systems Analysis, Laxenburg, Austria*

RR-85-7
July 1985

Reprinted from *Energy, The International Journal*, volume 10 (1985)

**INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS**
**Laxenburg, Austria**

## FOREWORD

Understanding agricultural policy options at national and international levels has been the major objective of the Food and Agriculture Program (FAP) of IIASA. The interactions of energy- and agriculture-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 these papers Jyoti Parikh and Gerhard Krömer, both former members of the IIASA Energy Program and now with the FAP, present a model for exploring energy and agriculture interaction and its empirical application to Bangladesh. The first paper provides a conceptual framework for the analyses of a number of issues concerning the pricing of fuels, fertilizer, and feed, the introduction of high-yield varieties, and the relevance of rural energy projects such as afforestation, bio-gas, charcoal kilns, improved stoves, the role of animal labor, etc. It also helps in understanding possible short-term changes that could be introduced in the rural energy and agriculture system and how they would affect different income groups in a rural economy.

The second paper describes an application of this framework to rural Bangladesh.

KIRIT PARIKH
*Program Leader*
Food and Agriculture Program

---

Reprinted with permission from *Energy, The International Journal*, 10, Jyoti Parikh, Modeling energy and agriculture interactions – I: a rural energy systems model; and J.K. Parikh and G. Krömer, Modeling energy and agriculture interactions – II: food–fodder–fuel–fertilizer relationships for biomass in Bangladesh


---

Printed by Novographic, Vienna, Austria

*Energy* Vol. 10, No. 7, pp. 793–804, 1985
Printed in Great Britain.

0360-5442/85 $3.00 + .00


# MODELING ENERGY AND AGRICULTURE INTERACTIONS—I: A RURAL ENERGY SYSTEMS MODEL†

JYOTI PARIKH
International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria

(*Received* 6 *December* 1983)

**Abstract**—Since many of the factors related to rural energy systems are gradually being quantified, there is a need to construct a model that integrates a number of these factors simultaneously in a consistent framework. Therefore, a general 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. 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 along with their assets, i.e. land holdings, livestock, etc. The by-products of agriculture, i.e. biomass, such as crop residues, animal dung, wood, etc., can be used to generate energy. On the demand side the use of them for feed, fuel, and fertilizer must be considered. Thus, the household sector (which is the largest user of noncommercial energy), as well as the rural industries sector, is intimately related to the agriculture sector. Twelve different energy sources and several conversion technologies, such as biogas, charcoal kilns, alcohol distilleries, etc., are considered. The model is applicable to low-income, biomass-scarce developing countries. However, different types of countries will require different approximations, and their needs for detailing some aspects or other may vary. The model is suitable for policy purposes because it considers several income groups separately and considers how different changes affect each of them.

## 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 crucial. Depending on the country, 30–70% of the intermediate input costs of agricultural crop production are directly or indirectly related to energy;[1] however, agriculture provides 20–90% of primary energy through the supply of noncommercial energy (wood, waste, dung, etc.).[2,3] This interactive system of energy and agriculture is shown in Fig. 1. It can be seen that energy for agriculture includes direct and indirect uses, *viz.* mechanization, irrigation, and fertilizers. It may be pointed out that in the developing countries the respective percentages of energy use for mechanization, irrigation, and fertilizers are 26%, 14%, and 60%. In Southeast Asia specifically, they are 13%, 20%, and 66%, respectively. Thus fertilizer production makes the largest single use of energy for agriculture. Pesticides, if separately accounted for, use 1–4% out of a total of 60%. 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.

Socio-techno-economic factors intertwined with the energy–agriculture systems are as follows: (a) In rural agricultural systems the animal dung and straw from crop residues are used for household cooking, linking the household energy sector very strongly to the fertilizer question. (b) The working cattle consume straw and waste, but provide services such as ploughing, irrigation, and transport, for which capital-intensive equipment such as tractors, pumps, and trucks would otherwise be required. However, unlike these machines that consume 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 to total bovines ranges from 30% to 50% in developing countries of Asia.[4] (c) Nearly 20–70% of total fertilizers applied come from organic fertilizers.[5]

† This work was funded by the Center for World Food Studies, Amsterdam.

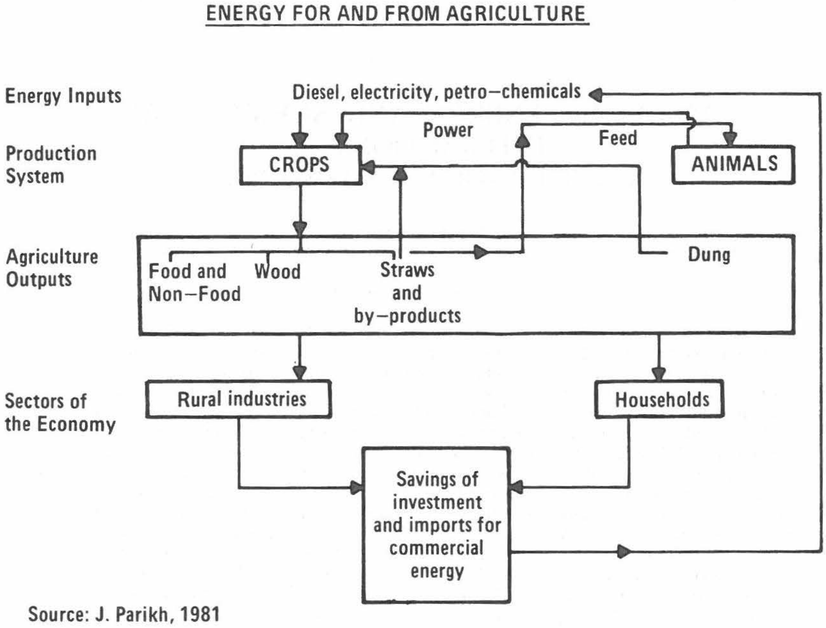


Fig. 1. Energy for and from agriculture.

However, the share of organic fertilizers is rapidly declining. This is because in some developing countries, like India, cattle population has nearly stabilized, and in some countries there is an annual growth of 1–3% at most. There is an emphasis on improving quality-more meat, milk, services—rather than increasing their number, and the large amount of biomass required to feed cattle is getting scarce. Thus, declining cattle growth and high growth rates in chemical fertilizers result in a declining share of organic fertilizers. On the other hand, in most developing countries,[6] even after 1973, the annual growth rates for the chemical inorganic fertilizer demands in many of the developing countries ranged from 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.[6] Therefore, a clearer understanding on issues related to choices of fertilizers 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, which implies the need for adequate and timely supply of electric, 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 70–90% of the rural population survives on agriculture[6] 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 technology.

While some efforts have been made by others[7,8] to elaborate and quantify some of the issues, this is an effort to link many of them in a modeling framework. This approach, which proposes a computerized model, has the advantage that many of the relationships between various components are tracked with a consistent set of assumptions, which is difficult to do manually. Moreover, a wide variety of changes in the system could be simulated.

1.2. *Problem statement and problem boundaries*

A model is formulated to discuss the following issues relevant for policy: (a) What are the implications of a given crop-allocation pattern 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? Here, land of various types (woodland, forest land, and fallow arable land) that can be allocated to energy crops (wood, cassava, and sugar cane for gasohol, etc.) need to be considered. (b) What are the effects of energy prices on choices of farming technology? (c) 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? (d) 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.? (e) What is the agricultural importance of working animals that 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.? (f) *Timely* availability of electric, diesel, or animal power is very crucial for groundwater 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 presently exists, and thereby to 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 a capital acquisition module is not constructed, although existing capital stock is given.†

## 2. MODEL DESCRIPTION

A linear programming model for the rural energy systems (RES) is constructed in order to capture interactions between crop and livestock production, organic and inorganic fertilizers, commercial and noncommercial 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 the following: several crop commodities; twelve activities of energy production and purchase, which include the production of primary and secondary energy products—e.g. charcoal, biogas, and gasohol—and final energy purchase; six activities of irrigation methods; twelve activities of fertilizer provision—i.e. four distinct activities, *viz.* purchases of chemicals, biogas, manure, and crop residues for each type of nutrients, nitrogen, phosphorus, and potassium; 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 availability 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 demands for cooking, lighting, and village industries are considered in competition with energy demands 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

† The model developed here is to be eventually linked to a detailed model of Bangladesh Agricultural Policy Model (BAM) being developed at the Centre for World Food Studies (CWFS) in the Netherlands. BAM is a year-by-year simulation model of the computable general equilibrium genre that 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, when extended, could look at medium-term options and policies and illustrate the dynamics of the system in more detail.

according to the agroclimatic conditions, and their initial pattern is the one that presently exists. Livestock is assumed to be given as present, and its maintenance is imperative. We maximize for the rural area

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

where $j$ = 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 ha, $p_c$ = price of crop $c$ per ton, $p_n$ = price of ton of fertilizer 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 (kL 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 tons by class $j$, $w$ = wage rate per day, $H_j$ = total human labor days required by class $j$, $H_{0,j}$ = own labor days put in by class $j$.

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 noncommercial 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 noncommercial energy resources are gathered, obtained in return of farm labor 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 biogas, 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 Appendix.

## 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 classes; (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 the total. All residues from different crops are added for a given income class $j$, which allocates them to the above uses depending on requirements and other opportunities.

## 5. LIVESTOCK SECTOR: MAINTENANCE AND SERVICES

Only cattle and buffaloes are considered in the model, because they have high feed requirements, 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. The equivalent animals are calculated by using 2 cows = 1 bullock = $\frac{1}{2}$ buffalo. Meat, milk, and other products given by animals are not considered because of the limited objective of studying only energy-related issues. Two types of animals are considered: working and nonworking. Their feed requirements, dung coefficients, and collection coefficients are different. A working animal, which is also a strong adult, eats 30–50% more than nonworking 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. The exogenously given share of the feed required for cattle could be obtained from pastures, and the remaining need is to be met from crop residues; when that is not sufficient, the feed could be bought. The calorie and protein contents of the available feed have to be greater than or equal to the required calories and protein by the animals. In addition to the feed, human labor required to maintain animals is considered. 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.

### 5.1. *Machinery versus 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 terms, so investment decisions are not made in the model. In the first instance, the behavior of the farmers in the short run is explored, for which a static model suffices.

Ploughing could be done by animals or by tractors of several types, whose stock is given *a priori;* each requires different amounts of human labor days, animal labor days, and diesel consumption per hectare of plowing. 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. Irrigation could be of two kinds: surface and ground water, which 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 irrigation 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 1. 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 seasons.

## 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: using crop residues—i.e. burning or plowing back straw on the ground—using dung, using biogas sludge, and purchasing chemical fertilizers. The first three provide organic fertilizers. The nutrient contents of organic fertilizers are given in Table 2. However, recall that the objective function minimizes only purchased commodities. Therefore, choosing the quantity of biomaterials for a particular purpose depends upon the relative prices of bought fuel, fodder, and fertilizers, and the demand for each. Shortfall in the demand is made up by the purchased fertilizers.

## 7. ENERGY FROM AGRICULTURE

### 7.1. *Energy supply side*

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

(a) five types of noncommercial energy sources are considered, which are gathered or produced within the agricultural system. These are dung, crop residues, and three types of fuelwood. Fuelwood 1 is gathered from homesteads (clusters of trees near houses),

† 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.

Table 1. 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 |

These numbers are suited to Bangladesh and may need to be changed for other countries.

3) Assuming a pair goes at 4 km per hour for 8 hours for pulling 0.5 t weight and 8 km per hour for empty trips (40 km). Human labor days are 50% of total days + time required for maintenance.
4) Assuming a truck has 3 to 5 ton capacity, going at 25 km per hour and 50% empty trips (only 12.5 km).
5) Assuming tractor carries 1 to 2 ton, goes at 10 km + 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.

requiring only labor. The upper limit of supply of fuelwood 1 is estimated from the area under it. Its productivity and heat values are low because they include twigs, branches, and barks. The supply of fuelwood 2 is obtained by employing human labor from natural forests. Its upper limit is specified by the area under forests multiplied by productivity. The heat value of fuelwood 2 is higher than dry matter collected around homesteads. Fuelwood 3 is harvested from wood plantations that are grown commercially, requiring investment, management, and perhaps transport. The heat value of this wood is the highest. Here, crop residues and animal dung are available to each income class according to their land and animal holdings, respectively, whereas fuelwood supply is a common property.

(b) Three types of secondary energy forms are considered: biogas, charcoal, and gasohol. They use the above-mentioned biofuels, which are processed through conversion facilities to obtain more efficient and high-valued secondary energy forms. A schematic version is illustrated in Fig. 2. These energy forms require initial investment, but in this static model they are considered after deriving their annual costs, assuming a certain rate of return (10%). Biogas, which produces methane from anaerobic digestion and sludge that could be used as fertilizer, has capital costs of about $250 (U.S.) for a 2-$m^3$/day plant.[10] 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 six tons of wood per ton of charcoal, and the kilns cost nearly $500 (U.S.). However, when the wood supply from forests is high (which is not the case in Bangladesh), this could be a practical solution for supplying a transportable and efficient energy source. 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 have agriculture surplus and are 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.

(c) Four types of commercial energy forms are considered, which are purchased with cash: kerosene, diesel, natural gas, and electricity. They are usually brought into rural

Table 2. Nutrient content 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/1000 $m^3$)† | 16.0 | 14.3 | 10.0 |

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

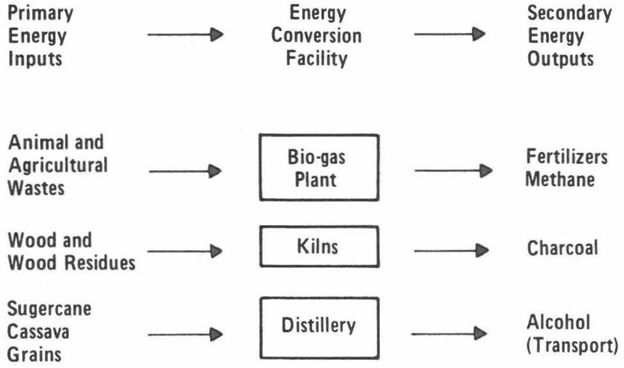


Fig. 2. Secondary and primary energy sources obtained from agriculture.

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 the rural population to pay for them with cash. These 12 categories of fuels have different heat contents and end-use efficiencies, which are listed in Table 3.

7.2. *Energy demand sectors*

(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, biogas, and electricity. 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 L of kerosene, 220 $m^3$ of biogas, 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

Table 3. 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 | 1000 $m^3$ | 25.4 | 0.55 | 0.55 | – |
| Gasohol | kilo lit. | 36.0 | – | – | – |
| Natural gas | 1000 $m^3$ | 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 | – | – | – |

Based on Kennes,[11] Islam,[12] and Islam.[13]

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 the nonagricultural 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 plowing, transport, and irrigation, are considered with other methods, such as animals, humans, or others.

## 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. 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.

Subject to data availability, the model could explore a number of policy implications relating to rural energy systems. For example, pricing policies of fuels, feed, fertilizers, or encouraging animal power versus tractors, or organic versus inorganic fertilizers. It can also give understanding of the dynamics of biomass allocation for food–fuel–fertilizers and other purposes, month-wise shortages and surpluses of biomass and their impacts on purchase of commercial energy, peak requirements of animal and human labor, etc. In addition to overall rural energy problems, it can also focus on special problems of landless and small farmers. Parikh and Krömer[14] have shown that in the case of Bangladesh the biomass allocation for food, fodder, fuel, and fertilizer is the most crucial question that is being picked up in the application of this model. This factor is also relevant for some provinces of China[15] and India.

## REFERENCES

1. J. K. Parikh, *Energy Systems and Development.* Oxford University Press, Daryaganj, Delhi (1980).
2. J. K. Parikh, Energy and agriculture interactions, in *Food for All in Sustainable World* (J. K. Parikh and F. Rabar, eds.). SR-81-2, International Institute for Applied Systems Analysis, Laxenburg, Austria (1981).
3. B. Stout, in collaboration with C. Myers, A. Hurand and L. Faidley, *Energy for World Agriculture.* FAO, Rome, Italy (1981).
4. H. P. Binswanger, *The Economics of Tractors in South Asia: An Analytical Review,* Agricultural Development Council and the International Crops Research Institute for the Semi-Arid Tropics, New York and Hyderabad, India (1978).
5. Food and Agriculture Organization (FAO), Organic materials as fertilizers. *FAO Soils Bulletin,* No. 27, Rome, Italy (1975).
6. Food and Agriculture Organization, *Production Yearbook,* Rome, Italy (1982).
7. A. Sfeir-Younis, *Energy and Development of Agriculture, A Review of the Issues.* AGREP Working Paper No. 76, The World Bank, Washington, D.C. (1983).
8. Food and Agriculture Organization, *Wood-Fuel Surveys.* GCP/IN71365/SWE, Rome, Italy (1983).
9. J. K. Parikh, *Energy* **4**, 989. Also presented at the U.N. University Conference at the East–West Centre, Honolulu, Hawaii (1979).
10. J. K. Parikh and K. S. Parikh, *Energy* **8**, 441 (1977).
11. W. Kennes, J. Parikh and H. Stolwijk, *Biomass* **4**, 209 (1984).
12. M. N. Islam, *Study of the Problems and Prospects of Bio-Gas Technology as a Mechanism for Rural Development.* Department of Chemical Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh (1980).
13. N. Islam and R. J. deLucia, *Energy Sector Planning in a Developing Country. Some General Needs and a Specific Approach in Bangladesh.* Presented at the World Energy Conference, Istanbul, Turkey (1977).
14. J. K. Parikh and G. Krömer, *Energy,* **10**, 805 (1985).
15. L. Ying Zong and Q. Xong, *Rural Energy Model for Yu Cheng County.* Report to the European Economic Commission, D.G.XII, Brussels, Belgium (1983).

## APPENDIX
## MATHEMATICAL DESCRIPTION OF THE MODEL

*Code to the symbols*

1. Activities are in capital letters. 2. The running index is indicated by a subscript. 3. The identification index is indicated by a superscript. 4. Coefficients are in small letters. The model could be run for a month or annually.

However, only the first constraint is illustrated with symbol $m$. In the rest of the equations, $m$ is dropped for convenience (except in the case of plowing 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, $r$ denotes crop residue; $f^r_{cb}$ = feed required in 1000 t of dry matter from crop residues per year by 1000 heads of animal type $b$; $N^r_{cmj}$ = crop residue in 1000 t 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 1000 t 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 $j$; $A_{bj}$ = 1000 animal type $b$ heads owned by class $j$; $Q^r_{cmj}$ = crop residues for crop $c$ in 1000 t 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 monthly. We use

$$\underbrace{-y_{cmj} * L_{cmj} * r_c}_{\text{crop residue production}} + \underbrace{F^r_{cmj}}_{\text{feed}} + \underbrace{N^r_{cmj}}_{\text{fields}} + \underbrace{Q^r_{cmj}}_{\text{households}} + \underbrace{O^r_{cmj}}_{\text{other purposes}} \le 0$$

for each income class $j$; $r$ labels residues. The total use of crop residues for cooking by all income classes is

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

2. *Animal feed balance.* $(\text{cal})^B$, $(\text{prot})^B$ = calorie and protein coefficients of bought feed in $10^9$ kcal and 1000 t of feed; $B^f$ = bought feed in 1000 t; $f^{\text{cal}}_b, f^{\text{prot}}_b$ = calorie and protein requirements per year for one animal in $10^6$ kcal and t, respectively; $A_b$ = 1000 animal heads of type $b$; $(\text{cal})^r$, $(\text{prot})^r$ = calorie in $10^6$ kcal/t and protein in $t/t$ of crop residues. Fixed amounts of $(\text{cal})^{\text{past}}$ and $(\text{prot})^{\text{past}}$ are obtained from grazing in pastures.

Calorie balance:

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

Protein balance:

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

$$-\text{ pastures } - \text{ purchased feed } - \text{ crop residue } + \text{ requirements} \le 0.$$

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; $Q^{db}_j$ = biogas 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 $j$th income class for cooking in t; $e^d_b$ = tons of dung required for 1000 $m^3$ of biogas.

$$\underbrace{- \sim\sum_b c^d_b d_b A_{bj}}_{\text{collected dung from animals}} + \underbrace{N^d_j}_{\text{manure}} + \underbrace{e^d_b Q^{db}_j}_{\text{biogas}} + \underbrace{Q^d_j}_{\text{household cooking by } j\text{th income class}} \le 0.$$

Total dung used for cooking by all income classes = $Q_2$:

$$\sum_j Q^d_j = Q_2.$$

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

4. *Fertilizer–nutrients balance.* $(\text{nut})^{d,n}$ = nutrient of $n$ type in t per 1000 t of dung; $(\text{nut})^{r,n}$ = nutrient of type $n$ in t of d.m. per 1000 t of crop residues; $(\text{nut})^{b,n}$ = nutrients of type $n$ in tons from 1000 $m^3$ of biogas; $F^n_{cj}$ = applied fertilizers on crop $c$ by class $j$ in t; $B^n$ purchased chemical nutrients in t; $N^b_{nj} = Q^{db}_j * (\text{nut})^{b,n}$; $N^d_n$, $N^r_n$, $N^b_n$, $B^n$ are activities of fertilizing with dung, crop residues, biogas sludge, and bought chemical fertilizers.

$$\underbrace{\sum_c F_{ncj}}_{\text{applied fertilizer}} - \underbrace{B^n_j}_{\text{bought chemical fertilizer}} - \underbrace{(\text{nut})^{d,n} N^d_{nj}}_{\text{manure}} - \underbrace{(\text{nut})^{r,n} * N^r_{nj}}_{\text{crop residues}} - \underbrace{N^b_{nj}}_{\text{biogas sludge}} \le 0.$$

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, since 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 also have to be region-wise. Moreover, upper limits for each type of irrigation method in terms of area have to be given.

6. *Energy balances for uses of energy.* $Q_k$ = energy production and purchase activities that are separate from utilization of it; $k$ = energy sources; production activities in physical units $u(k)$; 1 = crop residue 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, fertilizers, irrigation, labor) in t; 6 = charcoal in t; 7 = biogas 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)*

$$\sum_{k=1,12} -u_k^h * Q_{kj}^{ck} + u_j^{ck} \leq 0, \qquad \sum_j Q_{kj}^{ck} = Q_k.$$

$u_k^h$ = 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 $j$; $Q_{kj}^{ck}$ = energy source $k$ in $u(k)$ used in cooking by class $j$; $u_k^h = (\text{eff})_k^h * e_k$, where $(\text{eff})_k^h$ = efficiency with which energy source $k$ is used in households; $e_k$ = primary energy contained in energy source $k$ in $10^{12}$ J/$u(k)$.

6(b) *Rural lighting*

$$\sum_{k'} - u_{k'}^l * Q_{k'j}^l + u_j^{\text{light}} \leq 0.$$

$k'$ = 7, 10, 11 for biogas, kerosene, and electricity; $u_j^{\text{light}}$ = demand for lighting for exp. class $j$; $u_{k'}^l$ = effective number of households that could be satisfied with 1000 units of $k'$; because the three sources give qualitatively different lighting, the formulation has been made in terms of peoples' needs; $Q_{k'j}^l$ = activities of lighting with energy source $k'$ by class $j$.

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

$$\sum_{k'} p_{k'}(Q_{kj}^{ck} + Q_{k'j}^l) \leq b_j^h.$$

$p'_k$ = price of energy of type $k$ per physical unit (mu/$u(k)$); $b_j^h$ = household budget for fuel and electricity for $j$th exp. class in 1000 monetary units; mu = monetary unit.

6(d) *Requirements for village industries*

$$\sum_{k'} u_{k'}^{\text{VI}} * Q_{k'}^{\text{VI}} \geq u^{\text{VI}} * Y^{\text{VI}}.$$

$k'$ excludes gasohol; $u_k^{\text{VI}}$ = useful energy from each type of energy source utilised in village industries = ($\text{eff}_k^{\text{VI}} * e_k$) in $10^{12}$ J/$u(k)$, where $(\text{eff})_k^{\text{VI}}$ = efficiency with which source $k$ is used in village industries; $e_k$ is primary energy contained in source $k$ in $10^{12}$ J/$u(k)$; $Q_k^{\text{VI}}$ = quantities of energy of type $k$ used by village industries in $10^3$ $u(k)$; $Y^{\text{VI}}$ = value added in $10^6$ mu by village industries; $u^{\text{VI}}$ = useful energy in $10^{12}$ J/$u(k)$ taka of $y^{\text{VI}}$.

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*

$$\underbrace{\sum Q_{kj}^{c}}_{\substack{\text{sum of all households with}\\ \text{income class } j,\\ j,k=3,4,5 \text{ only}}} + \underbrace{Q_5^{\text{VI}}}_{\substack{\text{village}\\ \text{industries}}} + \underbrace{\frac{1}{(\text{eff})_{\text{ch}}} Q_6}_{\substack{\text{charcoal}\\ \text{production}}} \leq \underbrace{\sum Q_k}_{\substack{\text{wood from homesteads,}\\ \text{plantations and forests}\\ k=3,4,5}}$$

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

$$Q_4 \leq Y_F * F, \qquad Q_5 \leq Y_P * P, \qquad Q_3 \leq Q_A.$$

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)*

$$\underbrace{\sum_j Q_6^{cj}}_{\text{cooking}} + \underbrace{Q_6^{\text{VI}}}_{\text{vill. ind.}} \leq \underbrace{Q_6}_{\text{supply}}.$$

$Q_6$ is obtained from 7(a).

7(c) *Biogas conversion* (1000 L)

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

Activity already discussed in eqns 3 and 4.

7(d) *Alcohol conversion* (1000 L)

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

$\delta_c$ = 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 $m^3$)

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

Note. Because 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)

$$\underset{\text{bought}}{-B_k} + \underset{\text{households cooking + lighting}}{\sum_j (Q_{10,j}^c + Q_{10,j}^l)} + \underset{\text{village industries}}{Q_{10}^{VI}} \leq 0.$$

7(g) *Electricity balance* (1000 kWh)

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

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)

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

where $d_p$ = diesel required in $10^3$ L for 1000 ha of irrigated land; $d_T$ = diesel required in $10^3$ L for 1000 ha plowed by tractors; $d_t$ = diesel required for 1000 Tkm by tractors ($t$ = 2) and trucks ($t$ = 3); $D_e = G_d \times 0.25$ L (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 plowed with method two (i.e. tractors) in 1000 ha; for $(\text{Tkm})_t$ see equation below.

8. *Transport requirements (monthly basis).* $t$ = 1 bullock, 2 tractors, 3 trucks.

$$\sum_m \sum_t (\text{Tkm})_t = (\text{total production} - \text{self consumption in rural areas}) * \text{distance}$$

$$\geq \text{demand for transport in 100 Tkm} \geq \left(\sum_{cj} y_{cj} * L_{cj} - \sum_j n_j^{\text{rural}}\right) * a_d = \text{marketable surplus} * \text{average distance};$$

$n_j^{\text{rural}}$ = rural self-consumption for $j$; $a_d$ = assumed average distance of transport in kilometers; $(\text{Tkm})_t$ = distance travelled by each mode $t$ in 100 ton-kilometers (Tkm).

9. *Animal power requirements (monthly basis).*

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

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 animals of type $b$ per month; $a_m^l$ = animal days required for 100 Tkm; $L_{mp}$ = land plowed in 1000 ha by power $p$ ($p$ = 2).

10. *Tractor power requirements (monthly basis).*

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

$c_{mp}$ = tractor days for preparing 1 ha of land with tractor in month $m$; $a_m^2$ = tractor days for 100 Tkm in month $m$; $T_m = T/12$ = total number of tractors/12 months.

11. *Human labor constraint (monthly basis).* $H_m$, $O_m$, $M_m$ = month-wise labor availability, overwork and migration labor in days; $h_{mp}$ = labor days for plowing 1 ha by method $p$; $L_{mp}$, $L_m$ = land in 1000 ha plowed by method $p$ or irrigated by method $i$; $h_{mb}$ = labor days for maintaining 1 animal $b$; $h_{mt}$ = labor days for 1 Tkm by method $t$; $h_{mi}$ = labor days for irrigating 1 ha-m by method $i$; $h_{mk}$ = labor days for producing or converting 1 $u(k)$ energy type $k$.

$$\underbrace{-(H_m + O_m \pm M_m)}_{\text{available labor}} + \underbrace{\sum_p h_{mp}L_{mp}}_{\substack{\text{ploughing}\\ \text{with types } p}} + \underbrace{\sum_i h_{mi}L_{mi}}_{\substack{\text{irrigation}\\ \text{of types } i}} + \underbrace{\sum_b h_{mb}A_{mb}}_{\substack{\text{maintaining}\\ \text{animals}\\ \text{of types } b}} + \underbrace{\sum_k h_{mk}Q_k}_{\substack{\text{energy production}\\ \text{of types } k}} + \underbrace{\sum h_{mt}(\text{Tkm})_t}_{\substack{\text{transport of}\\ \text{types } t}} \leq 0.$$

12. *Land identity.*

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

Total land plowed = total land under crop = total land irrigated (including rainfed land). $L_{mp}$ = land plowed by $P$ in m, $L^{jcm}$ = land owned by each class $j$, $(ci)_j$ = cropping intensity by $j$, $L_{mi}$ = land irrigated (and rainfed).

*Energy* Vol. 10, No. 7, pp. 805–817, 1985
Printed in Great Britain.

0360-5442/85 $3.00 + .00


# MODELING ENERGY AND AGRICULTURE INTERACTIONS—II: FOOD–FODDER–FUEL–FERTILIZER RELATIONSHIPS FOR BIOMASS IN BANGLADESH

J. K. PARIKH and G. KRÖMER
International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria

(*Received* 6 *December* 1983)

**Abstract**—The model developed by Parikh[1] is applied to Bangladesh for which the situation in 1976–1977 is simulated first. This base case provides insights into the present behavior of different income groups with regard to choices of fuels and allocation of biomass for various purposes.

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 substantial amounts of fertilizers are used, the small and middle farmers would have feed and fuel shortages on adopting high-yielding varieties (HYV) that minimize straw–grain ratios. Similarly, by 1990, when the 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. Since Bangladesh is a very low-income and resource-scarce country, the choices of biogas, charcoal kilns, and alcohol distilleries, and the choices of mechanization, all of which require investment, play a minor role.

## 1. INTRODUCTION

Bangladesh provides one of the most relevant case studies for the application of the model described by Parikh.[1] In particular, the model could give insights into food–feed–fuel–fertilizer relationships because it provides an example where limited biomass resources need to be stretched to fulfill conflicting demands on them.

Bangladesh has one of the highest population densities in the world,[2] with 617 persons/km$^2$, i.e. 88 million over 144,000 km$^2$, in 1979.[3] Ninety percent of the population lives in the rural areas, where 93% of the household energy consumption is provided by biomass fuels, such as cow dung, straw, jute sticks, twigs, wood, etc. What is challenging is how a rural population of 73 millions obtains food, fuels, building materials (dung, straw, sticks, mud, etc.), and sustains 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 year from a high base of 88 millions, 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 $100 (U.S.) per person per year.

## 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 several studies. Bangladesh Energy Study,[3] 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 noncommercial energy use because of its importance, approaching it from the point of biomass availability. Tyers[4] mainly deals with investment planning for agriculture, particularly in irrigation and fertilizers. He takes the BES study as the basis for noncommercial energy data and elaborates on the agriculture sector and animate energy contributions. Briscoe[5] 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. Islam's[6] 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. A comprehensive summary of the above is made by Manibog,[7] 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 houehold energy at the aggregate *per capita* level. Household energy consumption patterns and income distribution at the national level are discussed only recently in a paper by Kennes *et al.*,[8] using the data of the household expenditure survey by the Bangladesh Bureau of Statistics (BBS). This study analyzes primary household energy data and assigns them to nine income classes: seven in rural areas and two in the urban areas.

The present paper begins where the study by KPS (1983) left off and reexamines some of the assumptions in a modeling framework where many of the interrelationships are more rigorously and consistently tied in. As can be seen later, this paper deals with many additional aspects, which, on cross-checking with other data, have firmed up a considerable number of parameters and give a more critical analysis of the data and relationships leading 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 by Parikh[1] are not included in the present version, which is meant for analysis of short-term issues only: (a) The 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 plowing 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 versus animal power, it would also demonstrate periodic surpluses and shortages of fuels and their effects on fuel substitution. (b) Since the emphasis here is on studying fuel–fertilizer–feed relationships, nonagriculture population is excluded. This could lead to a larger supply of biomass 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 few exceptions.

It is hoped that these issues, when analyzed later, will give additional insights. In particular, when investment is also considered in a dynamic model, 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. ANALYSIS OF HOUSEHOLD ENERGY DATA: BY INCOME GROUPS

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 landholding classes so as to make its relationship with agricultural assets and activities explicit (Stolwijk,[11] Kennes[12]). The distribution across classes is given in Table 1. Because 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

Table 1. People, households, and income; from Refs. 9, 12, and 13.

| Socio-economic group | People | | Households | | | Income | | |
|---|---|---|---|---|---|---|---|---|
| | 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 farmers I 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: Stolwijk,[9] Kennes,[12] Bangladesh Bureau of Statistics.[13]

urban-formal group includes people in government, industry, commercial, and service sectors.

A detailed analysis of household energy data is done in the KPS Study,[8] whose highlights are given below.

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. One third of the remaining 30% of the budget is allocated to household energy, leaving the remaining 18–23% of the total budget for clothing, housing, and other 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 some urban households only), 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.

Converting the quantity units into primary 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% jute sticks, 4% kerosene, and 1.6% electricity. However, there is a considerable difference between rural and urban energy consumption in amounts and patterns. The energy consumption pattern is shown in Fig. 1.

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

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

| | National use in million t† from BBS | GJ per quantity† | Assumed efficiency | National consumption TKJ ($10^{12}$ KJ) (primary) | Estimate by BES TKJ |
|---|---|---|---|---|---|
| Fuel wood‡ | 9.88 | 15.0 | 0.12 | 148.0 | 45.4 |
| Straw | 3.26 | 12.6 | 0.08 | 40.9 | 38.0 |
| Dung cake§ | 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¶ | 0.088 | 24.0 | 0.15 | 2.1 | – |
| Kerosene¶ (1000 lit.) | 390 | 35.0 | 0.35 | 13.6 | n.r. |
| Electricity¶ ($10^6$ kWh) | 189 | 10.5 | 0.80 | 2.0 | n.r. |
| Gas¶ (MCF) | 7700 | 9093 | 0.65 | 7.6 | n.r. |

† 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.

‡ BES data indicates fuelwood 7.4, twigs and leaves 19.0, and other fuels 19.0 MGJ.

§ Collection coefficient of 50% is assumed.

¶ 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, one finds, using these numbers, that the useful energy consumption indicated for each income class in Fig. 1 varies much less for different income classes than the primary energy consumption and falls in the narrow range of 0.52 GJ to 0.62 GJ per person.

## 4. CROP-RESIDUE PRODUCTION

Rice, wheat, and jute are the only three crops considered in the model, which in reality 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.

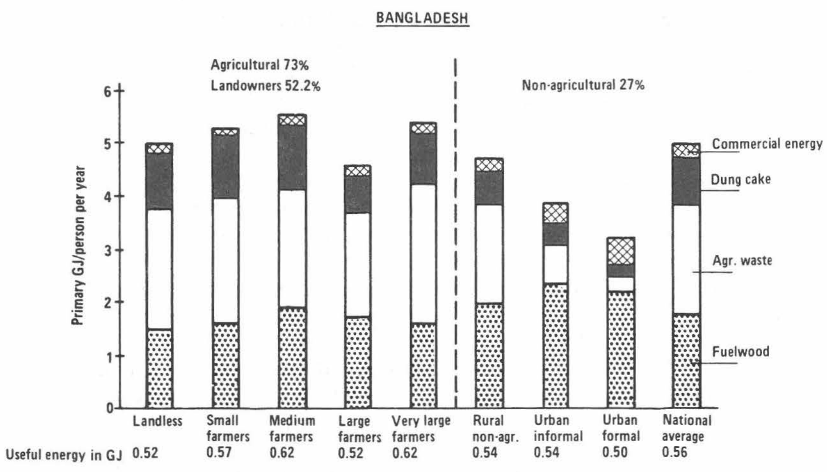


Fig. 1. Household use of primary energy by different income classes, 1976–1977.

Table 3. Crop-related data for Bangladesh 1976–1977.

| 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 | 1000 ha | | | |
| – 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 1.6 Mkcal/ton with protein content 35 kg/ton.

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. Crop-related data is given in Table 3.

## 5. LIVESTOCK SECTOR

The ownership of animals according to income groups is given by Stolwijk[11] and reorganized here in terms of working and nonworking animals, as shown in Table 4.

The working and nonworking animals are separated because of higher calorie intake of working animals and provision of services by the former. Calorie and protein requirements for nonworking animals, including calves, are taken to be 2.6 Mkcal and 80 kg of protein, respectively, and 3.8 Mkcal and 80 kg of protein for working animals.

Table 4. Livestock-related data 1976–1977, adapted to the model.

| Indicators | Units | Non-working cattle | Working cattle (incl. buffaloes)† |
|---|---|---|---|
| a) Ownership by income class | $10^3$ A | | |
| – 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 Table 5 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 amounts (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 overestimation, 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 feed, fuel, and fertilizer, and partly on matching assets (livestock, land), energy supply therefrom, and the energy demand by different income groups. The model results are described in three steps: (i) detailed description of the base run, which represents the situation in 1976; (ii) introduction of high-yielding varieties; (iii) increase in population in 1990.

### 7.1. *How does the present system behave?*

7.1.1. *Selection of the base run for* 1976. 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 reference system that describes the situation in 1976 as closely as possible.

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 since 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, twigs, and, to some extent, leaves); (b) increase in cooking efficiencies (which also leads to additional resources, since less resources are required for obtaining the given demand of useful energy); (c) increase in dung-collection coefficients for nonworking 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 feed. In other words, there was no case when supply of biomass was in excess compared to the needs.

Out of 50 runs carried out, some selected runs are reported fully in Table 6 and are described below.

*Run* 1. The base run is characterized by 10 Mt of total wood supply for cooking, 13 Mt of collected dung supply, 53 kg/ha of total fertilizer application ratio and fuel

Table 5. Nutrients from inorganic fertilizers in kg/ha.

| Farmer category | 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 private communication with H. Stolwijk.

Table 6. Base run (corresponding to 1976–1977) and variations of assumptions.

| Fuel | Base run† (1) | | Wood availability 8 mt (2) | | Dung availability 18 mt (3) | | Fertilizer rate reduced 33 kg/ha (4) | |
|---|---|---|---|---|---|---|---|---|
| *(Per capita energy for cooking)* | | | | | | | | |
| Crop residues (kg) | | 140 | | 165 | | 140 | | 140 |
| Animal dung (kg) | | 105 | | 129 | | 105 | | 105 |
| Fuelwood 1 (kg)‡ | | 64 | | 64 | | 64 | | 64 |
| Fuelwood 2 (kg) | | 97 | | 64 | | 97 | | 97 |
| *Commercial energy:*§ | | | | | | | | |
| Kerosene (l) | | 0 | | 0 | | 0 | | 0 |
| Electricity (kWh) | | 0 | | 0 | | 0 | | 0 |
| *Organic (dung + crop res. + biogas)*¶ | | | | | | | | |
| 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 residues (1000 t) | | 45723 | | 45723 | | 45723 | | 45723 |
| Fertilizer (%) | | 4 | | 4 | | 4 | | 4 |
| Fuel (%) | | 19 | | 23 | | 19 | | 19 |
| Feed (%) | | 61 | | 57 | | 61 | | 61 |
| Other (%) | | 16 | | 16 | | 16 | | 16 |

† 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.

‡ These two categories to be viewed together. The distinction between the two is explained in Part I, but not considered due to data limitation in all of these and subsequent runs.

§ Since this version of the model excludes energy for lighting and since the uses of natural gas, kerosene and electricity for purposes other than lighting in the rural areas are negligible, the base run shows virtually no use of these resources.

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

efficiencies as given in Table 2. The fuel–fertilizer ratio for the dung works out to be 50:50.

*Run* 2. Same as base run, except 8 Mt of total "wood" supply instead of 10 Mt. 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 nonworking animals 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,[7,8] but is probably unrealistic considering the age distribution of cattle and feed 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 (33 kg/ha instead of 53 kg/ha) fertilizer application rates, which reproduce actual purchase of chemical fertilizers reported for 1976–1977 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 feed and energy needs are met first, and then adjustments are made in the fertilizer sector. Thus, all the variations given above use about 6 Mt of dung for fuel first, and then use varying amounts of dung for fertilizer depending upon the availability.

Seen from another angle, we can use the model 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 ranges from 4 Mt/yr to 20 Mt/yr (BES). A special inquiry carried out by FAO puts these estimates around 6 Mt.[13] The results of the present model suggest that the wood supply has to be between 8 Mt to 10 Mt at least to meet other constraints that one has in the system. The fuel efficiencies of noncommercial 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 fuelwood, fuel efficiencies of the order of 10%, feed availability of about 1.4–1.7 t per animal, and dung collection of about 0.7 t per animal. Tyers[4] assumes 0.5 t per animal, which is too low. Manibog[7] and many others, including BES, on the other hand, assume only 35% of dung is used for fuel, but the present study puts it at much higher level—about 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 (40–50% of feed is converted into dung), and 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 four to five times more valuable at the prevailing prices of fuel and fertilizers in most developing countries than the 10 g of N, 6 g of P, and 12 g of K that it contains. Therefore, farmers prefer to burn dung and purchase fertilizers. These are also the conclusions of the recent study by Aggarwal and Singh, 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 of the following reasons: (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 as compared to using it for 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 of 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 minimize the effort of stocking. It is not likely that a woman will go several 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 0.9 t to 1 t of dung per animal leads to overestimation of dung up to 20 Mt. But when one considers that one-third of the animals are calves less than three years of age, and uses the norm of 0.7 t, then the total availability decreases to 13 Mt. When the supply was arbitrarily increased to 20 Mt in one run, the dung was used for burning and the rest for other purposes, there still

† 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.

Table 7. 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 | 53 | 53 | 68 |
| Crop residues (1000 t) | 45723 | 35552 | 43756 | 59440 | 43756 |
| Fertilizer (%) | 4 | 0 | 3 | 12 | 1 |
| Fuel (%) | 19 | 12 | 18 | 24 | 28 |
| Feed (%) | 61 | 67 | 62 | 49 | 51 |
| Other (%) | 16 | 21 | 17 | 15 | 20 |

† See footnotes for Table 6.

remained 6 Mt, as in the case of 13 Mt. Thus, 6 Mt is 35% of 20 Mt but 50% of the 13 Mt. 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 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 straw. However, HYV require much more fertilizer compared to the traditional varieties. If we assume 1 kg of fertilizer gives 10 additional kg grains, then a 100% increase in fertilizer levels in Bangladesh (from 33 kg to 66 kg) could lead to an increase from 1.5 t of paddy per ha to nearly 2 t/ha, i.e. a 30% increase. A 200% increase in fertilizers, i.e. 100 kg/ha leads to 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 and HYV scenarios are given in Table 3. The results are discussed below and summarized in Table 7. There are also other factors that increase yield, such as irrigation, soil improvements, etc., but only yield increases due to fertilizers are considered.

‡ Manibog[7] mentions that fuel value of jute is so valuable that fiber is considered a by-product. Tyers[4] finds that with increasing energy prices, rice-growing farmers switch to growing jute. The present model does not go into crop allocation and assumes it to be fixed.

Because 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* farmers switched to HYV, keeping other conditions of 1976 constant for runs (2), (7), (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 a 30% increase in yield due to HYV reduces the availability of crop residues from 45.5 Mt to 35.5 Mt. But when the fertilizer 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.

The most hurt are small farmers whose feed availability per animal is reduced to one-half in the second case [run (5)] and does not retrieve itself even in the third case [run (6)]. Medium-level farmers' feed availability is reduced by 15% in the third case. Large farmers have enough feed 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 increases at a rate of 3% annually. Increases of 20% and 40% over 1976–1977 figures are considered. How do the biomass 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 increases of 20% and 40%, respectively, are assumed to take place evenly in all classes, and questions related to diseconomies of scale for subdivided farms of smaller units are not considered. To feed this population somewhat better than today, a 60% increase in yields and a fertilizer application rate three times greater is assumed, the rationale for which is discussed in the earlier scenario. No increase in livestock is assumed, because they have been approaching a stable level for the last few years. (This is not true of goats, which are not in this energy model because they do not do farmwork.) The results of the two scenarios are summarized in Table 8.

It can be seen that a pattern similar to 1976–1977 could almost be managed 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), feed of the order of 0.8 t per animal would be required in order to replace the agricultural residues burned in the households. By this time the landless and small farmers as well as the middle farmers are vulnerable, not only in feed requirements but also in energy requirements. This is because with the same amount of land and animals, they cannot support a 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, since 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 Mt of fuelwood supply (for cooking only) going in the future may require afforestation programs, because, as shown by Douglas,[13] the present supply of about 10 Mt already comes from deforestation and is more than the natural regeneration limits.

## 8. FODDER–FUEL–FERTILIZER–RELATIONSHIPS IN AGRICULTURAL BANGLADESH: HIGHLIGHTS AND IMPLICATIONS

Fodder–fuel–fertilizer relationships are complex in the 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. The purpose of this study is threefold: (a) verification of

Table 8. Comparison of base run with high population scenarios in future.†

| Fuel | Base run (1) | | 30% higher yields without HYV + 20% more population (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 residues (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 | 4.0 | 4 | 3.1 | 3 | 6.7 | 7 |
| P in kg/ha (%) | 3.9 | 31 | 4.0 | 16 | 2.4 | 6 | 1.9 | 5 | 4.0 | 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 | 7.0 | 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 |

† See footnotes for Table 6.

existing data and identification of crucial parameters; (b) understanding of dynamics of interrelationships for different income groups; (c) insights into future developments.

Dynamics of the fodder–fuel–fertilizer interrelationships for 1976 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, 8–10 Mt wood supply, 10% fuel efficiencies for cooking, dung use for fuel–fertilizer 50:50, straw consumption per cattle 1.4–1.7 t per animal with dung output of about 0.7 t per animal, etc.

The dung will be used as manure only by those who, due to their income or fuel abundance, have other preferred fuels, but those who do not have alternative fuels would find it more economical in the short run to burn dung for fuel, rather than use it as fertilizer.

In fact, if nutrients are the only criteria for using manure (and not the humus and improvements of soil quality), then it would take four- to fivefold increases in fertilizer prices before the small farmers would switch from burning it to using it for fertilizer.

Regarding income groups behavior, our results show that subsistence-level households end up burning dung and sometimes straw. The reason for this is twofold: There is not enough biomass production available to the landless and small farmers to take care of the need for feed, fuel, and fertilizers for farmers who have less than 1 ha of land and one or two animals. In the case of straw, an additional use for it is feed for the animals, which is preferred to using it for fertilizer.

While changing to HYV for 20% additional yield or also when fuelwood availability is reduced from 10 Mt to 8 Mt, landless and small farmers 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 feed 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 are small in comparison with the biomass supply, there is enough available to feed the animals and for fertilizer. 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. We list some of the policy implications of this work for Bangladesh:

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

(b) If HYV are to be promoted, it would require a simultaneous support program for feed for the animals, especially for the small farmers, because they give 40% less crop residues. Additional feed would be necessary until fertilizer doses are 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 feed 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 necesssary. 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 in urban areas.

An even more comprehensive exercise for obtaining better insights into the role of animal power versus mechanization, month-wise shortages of fuels, the role of energy conversion technologies, such as biogas plants, charcoal kilns, alcohol distilleries, etc., is underway. The conditions for applicability to other countries are discussed earlier by Parikh.[1] 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 two billion people.

*Acknowledgments*—The model developed here owes much to the support provided by the Centre for World Food Studies (CWFS). Part of the data gathering was also completed with the support of the CWFS. The author is deeply indebted to M. Keyzer and W. 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. T. N. Srinivasan and J. P. Hrabovszky have critically gone through this manuscript and made valuable suggestions. J. Morovic helped to analyze 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 K. Parikh are gratefully acknowledged. We thank B. Riley and L. Roggenland for typing drafts of this manuscript.

## REFERENCES

1. J. K. Parikh, *Energy* **10,** 793 (1985).
2. World Bank Country Study, *Bangladesh—Current Trends and Development Issues.* South Asia Regional Office, World Bank, Washington, D.C. (1979).
3. *Bangladesh Energy Study* (BES). Montreal Engineering, Inc., Administrated by the Asian Development Bank, UNDP Project, BGD/73/038/01/45 (1978). Also R. DeLucia and H. Jacoby, *Energy Planning in Developing Countries: A Study of Bangladesh.* John Hopkins University Press, Baltimore, MD (1982).
4. R. Tyers, *Optimal Resources Allocation in Transitional Agriculture Case Studies in Bangladesh.* Ph.D. Dissertation, Harvard University, Cambridge, Mass. (1978).
5. J. Briscoe, *Population and Development Review* **5,** 615 (1979).
6. M. N. Islam, *Study of the Problems and Prospects of Bio-Gas Technology as a Mechanism for Rural Development.* Department of Chemical Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh (1980).

7. F. R. Manibog, *Bangladesh: Rural and Renewable Energy Issues and Prospects.* Energy Department Paper No. 5, World Bank, Washington, D.C. (1982).
8. W. Kennes, J. Parikh and H. Stolwijk, *Biomass* **4**, 209 (1984).
9. Bangladesh Bureau of Statistics, *Household Expenditure Summary of* 1976–77. Dhaka, Bangladesh (1980).
10. H. V. Asseldonk, D. Faber, W. Kennes, M. Keyzer, G. Overbosch, I. Rebelo, H. Stolwijk, W. Tims and W. van Veen, *A Linkable General Equilibrium Model for Bangladesh with Special Emphasis on the Agricultural Sector.* Centre for World Food Studies, Amsterdam, The Netherlands (1981).
11. H. Stolwijk, *Number of People per Socio-Economic Group.* SOW-81-4, Centre for World Food Studies, Amsterdam, The Netherlands (1981).
12. W. Kennes, *Food Expenditure Patterns in Bangladesh.* SOW-82-1, Centre for World Food Studies, Amsterdam, The Netherlands (1982).
13. J. Douglas, *Consumption and Supply of Wood and Bamboo in Bangladesh.* Field Document No. 2, FAO/UNDP/Planning Commission Project No. BGD/78/010, Supply and Demand of Forest Products and Future Development Strategies, Dhaka, Bangladesh (1981).