Assessing the Energy Potential of Agricultural Residues

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ABSTRACT

Most efforts in resource assessments involving agricultural wastes only evaluate the resource base and seldom determine the supply potential. This paper discusses a methodology that determines the supply potential of agricultural residues for use as fuel. The methodology takes into consideration the physical and social accessibility factors, the competing demands for the residue and the logistics of collection and utilization. The methodology has been successfully used to estimate the supply potential of rice residue for use as fuel in small West African country.

INTRODUCTION

In most developing countries fuelwood is the main source of energy. This is so particularly in the rural areas where nearly all the energy requirements of the domestic sector are met from this source. The demand for this type of fuel has led to an environmental crisis in these countries: forests have disappeared and deserts are gradually encroaching on woodlands. In some countries where this environmental crisis has already occurred, agricultural residues have now become an important alternative to fuelwood. In other countries where the environmental crisis has yet to occur, governments are actively considering policies that will keep the crisis away. Such policies will inevitably include re-afforestation, conservation techniques including the use of fuel-efficient technologies and the augmentation of fuelwood by agricultural residues. Thus, whether or not a fuelwood crisis already exists, it is important to know the available agricultural residues for possible use as fuel.

The assessment of the resource base of agricultural residues (i.e. the total amount of generated annually) is usually carried out on the basis of information on the crop-residue index and the total crop produced annually.[1,2] However, the estimation of the supply potential of these residues for use as energy sources is slightly more complicated because of the problem of estimating the fraction accessible.[3] The accessibility factor (i.e. fraction of resource base accessible) depends on the economic value of the residues as a fuel source, the cost of collection and the distribution of farm-community distances if the wastes are generated on the farm. Although there has been many reports estimating the resource base of agricultural residues,[4,5] up until now no well-defined methodology has been developed for estimating the supply potential.

This paper discusses an approach for estimating the supply potential of agricultural wastes as a potential source of energy. It is then applied in a case study where the supply potential of rice residue in Sierra Leone, a small West African country, is estimated.

METHODOLOGY

Introduction

Biomass resources assessments distinguish between two levels of assessment: resource base (stock or yield) and supply potential. The latter is a fraction of the former and is the focus of our attention here. In this work we also recognise two classes of agricultural residues: those generated on the farms (on-farm residues) and those generated off the farms during processing (off-farm residues). In general, the resource base and the supply potential for off-farm residues such as rice husk are the same when the residue is used as fuel in the domestic sector. This is because the off-farm residue is usually generated within the community and hence the problem of accessibility does not exist; in this case the entire resource base will be accessible.

Principle of the Methodology

The methodology used in assessing the supply potential of agricultural residues is an extension of that which was discussed by Massaquoi.[6] First, the amount of residue generated annually (e.g. the resource base) is estimated from statistical data on primary crop production and field data on residue index. The latter is the ratio of residue to the primary crop. Once the resource base is known, the main task will be to determine the fraction of the resource that is accessible and the amount that is required for non-energy uses.

In order to determine the fraction of the resource base that is accessible, it is essential to know the economic value of the residue. High economic value will encourage consumers to go longer distances to collect the material or offer the farmer higher prices for it; while lower values will reduce the quantity that is accessible. Another important parameter in estimating the physically accessible residue is the production (or collection) cost of the residue. This is a function of the distance between the residue generation point and the utilisation point (or the community). The production cost at different farm locations is compared with the economic value of the residue. If the production cost is greater than the economic value then the residue generated at the particular location will not be physically accessible. The maximum collection distance also referred to as the radius of the collection area, is the distance at which the collection cost is just equal to the economic value of the residue.

Once the maximum collection distance is known, the next step is to determine the distribution of the distances between the generation point and the community. This is done through a sample survey. Combining this information with that on the maximum collection distance, one will be able to estimate the fraction of residue accessible. The distribution of distances will reveal the quantity of residue lying at locations with distance less than the maximum collection distance and this represents the amount physically accessible.

Some of the residues that are physically accessible may not be available because of socio-economic factors such as the land tenure system, secret society land area, etc. The fraction of the physically accessible residue that is not available because of such socio-cultural factors is evaluated from field survey.

The residue may also be used for non-energy purposes such as animal feed or fodder. The quantity of residue used for non-energy purposes is determined from statistical records. If the economic value for other uses is higher than that for energy use, then the biomass available for energy use is the total available biomass less that which is required for other uses. If again the economic value for other uses is less than that for energy use, then all the available biomass could be used for energy purposes because it is assumed that energy-use will be given preference. For the special case of rice husk, it was learnt that the generation points were within the community and hence the collection cost was not a function of distance. In this case all the husk generated was considered physically accessible. This is generally true for all residues generated in crop processing industries.

Use of an Information Flow Diagram

An information flow diagram depicting the important items of information required in the methodology is given in Fig. 1. There are two categories of information sets in the diagram: those which must be determined from research (i.e., the primary information) and those to be calculated from combinations of the primary information. In this section we discuss the primary items of information and how they can be obtained. In the succeeding section the equations for combining them to obtain the secondary items of information are discussed.

The following input data have to be collected from either statistical records or field surveys in order to use the methodology: annual production of primary crop, the residue index, physical characteristics of the residue, the cost of collecting the residue, the distribution of farms-community distances, the quantity of residue used in non-energy activities, the economic value (or price) for use in non-energy activities, the energy conversion efficiencies of the different end-use technologies, cost parameters of the end-use technologies and the socio-cultural constraints on the accessibility of the residue.

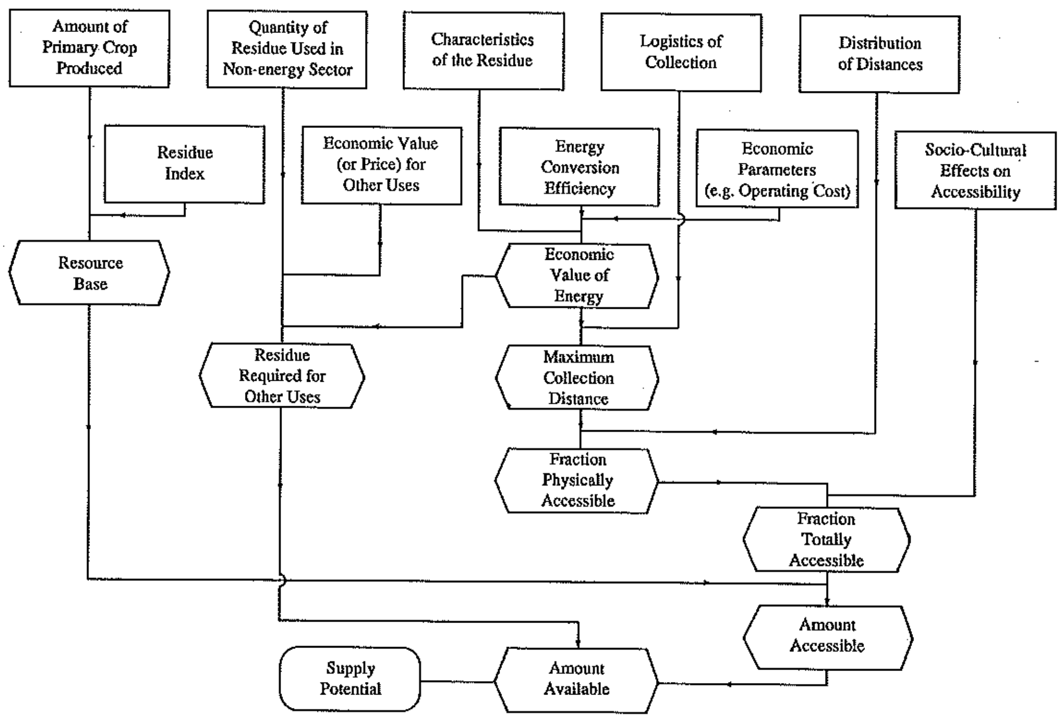

Fig. 1. Information flow diagram depicting information required to assess the energy potential of agricultural residues.

Primary crop production

This piece of information is usually obtainable from statistical records. If such records do not exist, one can use the data on land use pattern and crop yield to obtain this information. Thus, the primary crop produced annually is the product of the crop yield per hectare and the total land area covered by the crop.

Residue index

This is the ratio of the amount of residue generated to the amount of primary crop produced. The primary crop is that part of the plant for which it is grown. For example, in the case of the rice plant the grain is the primary crop.The residue index is usually determined from field data.

Physical characteristics of the residue

The main characteristics of the residue that will be useful in the resources assessment are the bulk density and the calorific value. There are standard laboratory methods for determining these quantities. The net calorific value is usually preferred over the gross calorific value.

The cost of collecting the residue

On-farm residues require collection from an extensive area. Utilisation of the residue off-site, implies that the residues must be purchased from the farmer by an outside operator and allowance must then be made for a profit to the farmer and transportation from farm to the energy end-user. Moreover, the energy demand may be all the year round while the wastes may only be available at a particular time of the year. Storage is therefore another added cost. This includes the cost of handling and the capital invested in the storage facility. Storage and transport costs are both related to the physical characteristics of the residue.

The total cost will comprise of the purchase cost, the cost of gathering and loading, transportation cost and storage cost. The transportation cost usually varies linearly with the distance of the round trip. Usually the cost of gathering the residue into a single location on the farm is included in the purchase cost. A survey of opinion will be useful to determine these cost parameters.

The distribution of farm-community distances

A survey is usually carried out to find out the number of farms located at various distances.

Quantity of residue used in non-energy activities

These data can be computed from statistical records in cases where the residue is used in the formal sector. If the residue is used in an informal way, such as ploughing back into the land, the amount used can be computed by assuming that the residue generated by such farmers are all used in non-energy activities.

Price (or economic value) of the residue when used in non-energy activities

This refers to the present value of the residue if it is used in the non-energy sectors such as agriculture. If it is already used in an informal manner then the economic value (i.e. opportunity cost) for its use in that way is determined. If it is used in the formal sector then the price paid for it is obtained from interviews.

Energy conversion efficiencies of the different end-use technology

The economic value of the residue will depend on the efficiency of the end-use technology.This efficiency depends on the type of fuel. If the residue is being considered for augmenting fuelwood, then the end-use technology in question is mainly cooking stoves. There are standard laboratory experiments for determining stove efficiency where such information is not available from the literature.

Cost parameters of the end-use technologies

This includes the operating and capital costs of the technology. They can be estimated from the cost of time to complete a typical operation and the cost of materials used in the construction.

Socio-cultural constraints on the accessibility of the residue

A survey is usually carried out to find out if there are any religious, or cultural reasons for not wanting to use particular residue as fuel. The value of the fraction of the population who object to the use of the residue as fuel is obtainable from such surveys.

Calculation Procedure

The calculation procedure and the equations used in estimating some of the secondary information depicted in the information flow diagram are presented in the following paragraphs. Details of the development of these equations are given by Massaquoi.[7]

Resource base

The primary items of information required for the estimation of the resource base are the total amount of the primary crop produced annually and the residue index (or wasted factor). When detailed crop production statistics are not available, the latter can be obtained from the land use pattern and the crop yield. Thus the resource base R_B is given as :

$$R_B = R_i P \qquad (1)$$

where R_i is the residue index, and
P is annual production of the primary crop.

Economic value

Most attempts at estimating biomass fuel value have typically considered the energy of the material as a joule-for-joule replacement for coal or oil without considering the capital cost penalties associated with the biomass system. Moreover, even the differences in conversion efficiency and the logistics of utilisation such as the high operating cost are ignored. The approach used here is to determine the economic value in terms of the quantity of conventional fuel saved.

The items of information required for estimating economic value of the residues are the annual operating and capital cost of end-use technology for both the residue and the conventional fuel for which it is to be substituted. Massaquoi[7] and Tillman[8] have developed an expression for the economic value of biomass fuel as:

$$V_E = \frac{\Delta C_c + \Delta C_o + P' W'_f}{H_{net,r}\, \eta_r\, W'_f} \tag{2}$$

where
V_E is the economic value per unit weight of residue when used as fuel,
ΔC_c is the difference in annual cost of capital between conventional fuel and residue-fired stove = $(C'_c - C_c)$,
C'_c, C_c are respectively the annual cost of capital for conventional fuel and residue-fired end-use technologies,
ΔC_o is the difference in annual operating cost between conventional fuel and residue-fired stove = $(C'_o - C_o)$,
H'_{net}, H_{net} are the net calorific values of conventional fuel and residue,
$H_{net,r}$ is the ratio of the net calorific value of conventional fuel to that of the residue (H'_{net}/H_{net}),
η' and η are respectively the thermal conversion efficiencies of conventional fuel and residue fuels,
η_r is the ratio of the efficiencies of the conventional fuel to that of the residue (η'/η),
P_f is price of fuel, and
W_f is weight of fuel used.

Maximum collection distance

The maximum collection distance is determined by the total collection (or production) cost and the economic value of the residue. The collection cost is directly proportional to the distance between the farm and the community when the residue is generated on the farm. The following equation has been developed for the total cost for on-farm residues.

$$C_R = C_T L + C_S + C_F \tag{3}$$

where
C_R is the total cost of the residue per unit weight,
C_S is storage cost per unit weight,
C_T is the transportation cost of one unit weight per unit distance,
C_F is fee paid to farmer to gather the residue in one post on the farm, and
L is distance between producer and consumer.

The maximum collection distance, L*, is the point at which the collection cost just equals the economic value of the residue. In mathematical terms:

$$V_E = C_T L^* + C_S + C_F \tag{4}$$

or

$$L^* = \frac{V_E - C_S - C_F}{C_T} \tag{5}$$

Fraction of residue physically available

One of the primary items of information required for the methodology is the distribution of farm-community distances. From these data it is possible to construct the cumulative distribution function which will show the fraction of farms at distance less than or equal a certain figure, $F_X(L)$. From this distribution it is possible to obtain the fraction of farms accessible $F_X(L^*)$ (i.e,. the fraction of farms located at a distance less than or equal to the maximum collection distance L^*). If the size distribution of farms is independent of distance then the fraction of farms accessible is the same as the fraction of residue accessible.

Fraction totally accessible

Access to the residue is both from the point of view of location (physical accessibility) and socio-cultural condition (social accessibility). The latter is estimated from field survey. Thus the fraction of residue accessible, F_A, is given as :

$$F_A = F_X\,(L^*)\ F_S \qquad (6)$$

where F_s is the fraction of residue accessible from the socio-cultural point of view, and $F_X(L^*)$ is the fraction physically accessible.

Amount of residue accessible

The total amount of residue accessible is given as :

$$R_A = F_A\,R_B = F_A\,R_i\,P \qquad (7)$$

Combining Eqs. (6) and (7) results in

$$R_A = F_X(L^*)\ F_S\ R_i\ P \qquad (8)$$

for off-farm residue $F_X(L^*)$ is approximately unity.

Amount of residue available for other uses

Residue may also be used for non-energy purposes such as raw material for industry. If the economic value (or current price) of the residue when used in non-energy operations is considerable more than that for energy then the former will get priority for the residue. If on the other hand the reverse is the case then all the accessible residue is considered available for use as fuel.

Thus the total residue available for use as fuel is given as:

$$\begin{aligned} R_{AV} &= R_A - R_O \quad \text{if } V_{EO} > V_E && \text{(a)} \\ &= R_A \qquad\quad \text{if } V_{EO} < V_E && \text{(b)} \\ &= 0 \qquad\quad\ \ \text{if } V \;\; < V_{EO} \text{ and } R_O > R_A && \text{(c)} \end{aligned} \qquad (9)$$

where R_{AV}, R_A, R_O are, respectively, amount of residue available, amount accessible and the quantity used for non-energy activities, and
V_{EO} is the economic value of the residue in non-energy activities.

Supply potential

On a weight basis, the supply potential S_p is equal to the resource available R_{AV} or

$$\begin{aligned} S_P &= R_A - R_O \text{ if } V_{EO} > V_E && \text{(a)} \\ &= R_A \quad V_{EO} < V_E && \text{(b)} \\ &= 0 \quad V_{EO} > V_E \text{ and } R_O > R_A && \text{(c)} \end{aligned} \tag{10}$$

Combining Eqs. (8) and (10) results in the following expression for supply potential in terms of the primary information.

$$\begin{aligned} S_P &= F_X(L^*)\ F_S\ R_i\ (P - R_O) \text{ if } V_{EO} > V_E && \text{(a)} \\ &= F_X(L^*)\ F_S\ R_i\ P \quad \text{if } V_{EO} < V_E && \text{(b)} \\ &= 0 \quad \text{if } V_{EO} > V_E \text{ and } R_O > R_A && \text{(c)} \end{aligned} \tag{11}$$

APPLICATION OF THE METHODOLOGY

The methodology described in the preceding sections was used to estimate the supply potential of rice residues as fuel in Sierra Leone, a small country in West Africa. There are two types of rice residue: rice husk and rice straw. The former is normally generated off-farm during processing while the latter is generated on-farm during harvesting.

Country Background

The Republic of Sierra Leone is in West Africa situated between latitude 3° and 10°N. The total land area is 71,700 km² with an estimated population of 3.7 million. Agriculture is a major sector of the economy and rice, the staple food of the population, is the biggest annual crop. It is therefore, expected that the residues emanating from rice farming will be considerable. A study was therefore carried out to find out how much is generated annually and the fraction of the total that is available for use as fuel. The study looked at both types of rice farming practices prevalent in the country, i.e. farming on dry land (upland farming) and farming on swamp land.

Data Input and Sources

Table 1 shows a summary of the data used in the assessment of the supply potential. The methods of evaluating these data are discussed in the references in Table 1.

For rice straw, which is an on-farm residue, the distribution of distances between the farm and the community is essential for establishing the fraction that is physically accessible. Table 2 gives the average number of farms located at various distances. These figures are approximations based on replies to the questionnaire and measured time to arrive at each farm. Since most people walk to their farms, it is observed that the longest distance from the edge of the community to the farm is just over

Table 1. Data for estimating supply potential of rice residues for use as fuel in cooking stoves.

Item	Value	Unit	Source of information
Primary Crop Production			
Upland rice	400 536	tonnes	Ref (9)
Swamp rice	155 464	-	
Total	556 000	-	
Residues Index			
Rice husk	0.325	(tonnes/tns.)	Ref (6)
Rice straw (swamp)	3.8	-	
Rice straw (upland)	3.37	-	
Weighted average for straw	3.58	-	
Physical Characteristics			
(i) *Rice husk*			
Density	107	kg/m^3	Ref (6)
Ash content	20.3	%	
Net calorific value	12125	kJ/kg	
Moisture content	11.87	%	
(ii) *Rice straw*			
Density (bulk) compacted	320	kg/m^3	Ref (6)
Ash content	17.9	%	
Net calorific value	11381	kJ/kg	
Moisture content	17.91	%	
Collection Cost Parameters			
Rice straw			
Storage	1.0	US$/tonne	Ref (7)
Gathering	2.3	US$/tonne	
Transportation	2.6	US$/tonne/km	
Cost of Utilisation			
Difference in annual capital cost of stoves (ΔC_c)	0.0	US$	Assumed
Difference in operating times between rice husk stove and wood stove	1.5	hrs	Ref (7)
Difference in operating time between banded straw stove and wood stove	0.0	hrs	
Ratio of conversion efficiencies η_r	1.0	-	Assumed

2.5 km. It was found that the distribution could be approximated to a normal probability density function with a mean of 1.4875 km, and standard deviation of 0.531 km.

This information was used to construct the cumulative distribution function $F_X(L)$, which defines the fraction of farms located at a distance less than or equal to a certain value.

The use of rice residues for non-energy activities was also investigated. Other uses of rice husk in Sierra Leone are not yet significant. However, in the case of rice straw it was discovered that although there is no significant conscious use of this residue at the moment, its removal from swamp lands will lead to serious deterioration of the swamp in the long run. Thus, it is concluded that the amount of rice straw corresponding to that generated on swamp farms is used for non-energy activities.

The economic value of the straw as a soil fertiliser for swamp land was not evaluated but deemed to be much higher than that for the straw as an energy source.

Finally, the survey of opinion did not reveal any social or cultural prohibitions or inhibitions against the use of the rice residues. Details of the questionnaire are presented in the appendix.

Results of the Study

Resource base

Applying Eq. (1) and using the data of Table 1, we find that the total rice straw generated annually is 1,962,680 tonnes (air dried wt.) or 1,611,360 tonnes (oven dried wt.). This amount consists of 548,787 (air dried) generated on swamp and 1,413,893 tonnes (air dried) generated on upland farms. The total amount of rice husk, all of which is generated off the farm, is estimated at 180,700 tonnes (air dried wt.) or 159,380 tonnes (oven dried wt.).

Economic value of the residues

Equation (2) and the data given in Table 1 were used to obtain the economic value of the residues. Of course the economic value of the residue will depend on the end use. In this case, since the residues are most likely to be substitutes for fuelwood in stoves, their economic values as fuels in cooking stoves has been estimated.

Table 2 gives a summary of the economic values of the residues. It is noted that for rice husk the economic value as briquettes is far higher than that for the ordinary pulverised husk. In fact, in Sierra Leone pulverised husk has little economic value as fuel for domestic cooking. For large operations such as the parboiling of rice paddy, the value of rice husk is considerably high. It is assumed that rice straw is only used in compact form hence only the economic value of banded straw is given.

Table 2. Summary of the economic value of rice residues as substitute fuel for wood stoves (Note: Price of fuelwood is US$17.00/tonne).

Type of activity	Average amount of fuelwood used per year (tonne)	V_B of rice husk briquettes in wood stove (US$/tonne)	V_B of pulverised rice husk in packed bed stoves (US$/tonne)	V_B of banded straw in wood stove (tonne)
Normal domestic cooking (small)	2.4	13.0	0.0	12.0
Domestic cooking (large)	3.6	13.0	3.0	12.0
Small-scale industries	10	13.0	10.0	12.0

Maximum collection distance for rice straw

Since straw is generated on the farm, there is a maximum distance one has to go to collect it. Beyond this distance it is uneconomic to collect it for use as fuel. This distance was estimated using Eq. (5) and the figures for the economic values in Table 2 together with the collection cost parameters of Table 1. The maximum collection distance for rice straw is 1.9 km.

Fraction of rice straw physically accessible

Table 3a gives the distribution of distances between farms and communities. The cumulative distribution of distance $F_X(L)$between farms and communities was also developed using the data of Table 3a. Since the maximum collection distance (L*) is 1.9 km, the fraction of farms less than or equal to 1.9 km. (i.e. $F_X(L^*)$) is given as 0.80 (see Table 3b). This is the fraction of straw physically accessible.

Table 3a. Frequency of occurrence of the different distance ranges.

Range of distances	< 0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0
Mean of Range x_i	0.25	0.75	1.25	1.75	2.25	2.75
Frequency f_i	5	15	42	39	16	2

$$\overline{X} = \frac{\Sigma f_i X_i}{\Sigma f_i} = 1.4685, \; S = 0.53138, \; n = 119$$

Supply potential

Rice Husk - Since there is no other major economic use for rice husk, R_0 is zero and Eq. 11(b) is used to find the supply potential. Furthermore, it was mentioned that nearly all the husk generated is within the community, hence it is very accessible.Therefore the accessibility factor ($F_X(L^*)$), is one. Also the social access problem was found to be non-existent (i.e. $F_S = 1.0$).

Thus Eq. 11(b) reduces to

$$S_p = R_i P$$

Using the above equation it was found that the supply potential of rice husk is 180,700 tonnes (air dried wt.) or 159,380 tonnes (oven dried wt.).

Rice Straw - For rice straw the accessibility was estimated as 0.8. As stated earlier that all straw generated on swamp land will be considered unavailable since its economic value as fertiliser for the swamp (i.e. V_{EO}) is much greater than that for use as fuel (V_E). The total amount of straw generated on swamp land is 548,787 tonnes (air dried). This amount is less than the total resource base and we can therefore apply Eq. 11(a).

Table 3b. Cumulative distribution of distances between farms and communities, using standardised normal distribution with variable $(\frac{X - \mu}{\sigma})$.

Distance L	$K = (\frac{L - \mu}{\sigma})$	Fraction of farms located at distance less than or equal L ($F_x(L)$)
0.1	-2.5733	0.00508
0.2	-2.3871	0.0086
0.3	-2.1989	0.014
0.4	-2.010	0.0222
0.5	-1.88226	0.0344
0.6	-1.6344	0.0516
0	-1.258	0.105
1.0	-0.8816	0.189
1.2	-0.50528	0.308
1.4	-0.1289	0.4487
1.5	0.05927	0.524
1.6	0.24746	0.6
1.8	0.6238	0.7324
2.0	1.00	0.8413
2.2	1.3766	0.914
2.4	1.7529	0.96
2.6	2.1293	0.98
2.8	2.5057	0.99
3.0	2.8821	0.998

Thus

$$S_p = F_X(L^*) \; F_s \; R_i \; (P - R_o)$$

where $F_X(L^*)$, F_s, and R_o are 0.8; 1.0; and 548,787 respectively.

The supply potential of rice straw is therefore 1,062,573 tonnes (air dried wt.).

CONCLUSIONS AND SIGNIFICANCE

The use of agricultural residues as substitute for fuelwood is considered essential for the preservation of forests and the overall protection of the environment. In order to develop any policy on the use of residues it is essential to know the supply potential. However, existing methodologies only determine the resource base which is usually considerably more than the actual supply potential. This paper has presented a detailed step-by-step approach of how to determine the supply potential using statistical data, information from scientific literature and data collected in the field. The methodology has been tested in a small West African country where the execution of the various steps has been amply illustrated. A summary of the results and typical values of the parameters is given in

Table 4. It is concluded that this methodology can be used to assess both on-farm residues (e.g. rice straw) and off-farm residues (e.g. rice husk).

Table 4. Summary of Results.

Item	Symbol	Value for rice straw	Value for rice husk
Resource base (air dried weight)	R_B	1,962,680 tonnes	180,700 tonnes
(oven dried weight)		1,611,360 tonnes	159,380 tonnes
Maximum collection distance	L*	1.9 km	-
Fraction physically accessible	F_x (L*)	0.8	-
Social Accessibility Factor	F_s	1.0	1.0
Supply potential (air dried weight)	S_p	1,062,572	180,700

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NOTATIONS

C_c	Annual capital cost of residue end-use technology
C_F	Fee paid per unit weight of residue gathered on the farm
C_O	Annual operating cost of residue end-use technology
C_R	Total cost of residue/unit weight
C_s	Annual storage cost/unit weight
C_T	Transportation cost/unit weight and distance
f_i	Frequency of occurrence of a particular range of farm-community distance
F_A	Fraction accessible both from point of view of location and socio-cultural constraints
$F_X(L)$	Cumulative distribution function
$F_X(L^*)$	Fraction physically accessible
F_s	Fraction socio-culturally accessible
H_{net}	Net calorific value of conventional fuel (kJ/kg)
$H_{net,r}$	Ratio of net calorific value of residue and conventional fuel
L	Distance between farm and community (km)
L^*	Maximum collection distance (km)
n	Sample size
P	Annual production of primary crop (tonnes/yr)
P_f	Price of conventional fuel per unit weight
R_A	Total quantity of residue accessible (tonnes/yr)
R_{AV}	Residue available
R_B	Resource base
R_i	Residue index - the ratio of residue to primary product
S_p	Supply potential
V_E	Economic value of residue as an energy source
V_{EO}	Economic value of residue in non-energy activities
W_f	Average annual weight of fuel used
$\overline{X}$	Sample mean
X	Random variable representing farm-community distance

Superscript

(') denotes conventional fuel

Greek symbols

ΔC_o	Difference in annual operating cost of conventional and residue-fired stove
ΔC_c	Difference in annual cost of capital of conventional and residue-fired stove
η	Thermal conversion efficiency
η_r	Ratio of thermal conversion efficiencies of conventional and residue fuels
σ	Standard deviation
μ	Mean.

APPENDIX
Energy Supply Potential from Rice Husk and Rice Straw
Questionnaire on Logistics of Collection

Enumerator Code....................
Respondent Code ....
Name of Village/Town ....
Estimated Population of the Village/Town....................

A. Background

1. Type of farm ....Family.....................................
   Co-operative..Large commercial......................................
2. Type of farm ....upland ....swamp
3. What is the quantity of husked rice produced annually ....(bushels,75kg bags, tonnes, others)...
4. What is the method of harvesting the rice?.................mechanical ....manual
5. What is the method you use for milling the rice?.....................mechanical ....manual
6. What method do you use for threshing?.................mechanical ....manual
7. How many people are in your household? ....
8. What type of fuel do you use for cooking?...........wood ....charcoal.............agricultural residue...........other (specify) ....
9. Do you parboil your husk rice? ....yes.........no
   If yes,what fuel do you use ....wood ......agricultural..............other.
10. Do you buy fuel? ....yes...........no
    If yes, how much do you pay for the fuel?..................
    If no, how far do you go to fetch fuel?............................; and how much time do you spend in gathering wood ....(man hrs/day, man hrs/week)

B. Location of Waste Accumulation Point

1. Are all your straws generated at a single location?...............yes..............no
2. Indicate how much of the straw is generated at each of the following locations:
   (all, half, quarter).................... left on farm land..................farm house......................
   at home in the back yard...................other (specify)
3. Is all the husk generated in a single location..............yes..............no
4. Indicate the quantity of husk generated at each of the following locations (all, half, quarter) ....on the farm ....off the farm.

C. Distances

1. How far is your farm from the town/village? ....miles or ....hours of walk ing
2. Does your town have a commercial fuel market?..........yes..........no
   If no, how far is the commercial fuel market?..........miles
3. If you use mechanical mills for dehusking the rice, how far is the mill from you? ....miles and how far is it from the nearest commercial fuel market..............miles

4. Is the farm along the motor road?.............yes...............no
5. How do you transport things from the farm to the community?...

D. Current Uses of the Rice Husk/Straw

1. What do you do now with your husk?..........throw away..........use as fuel ....animal feed ......other (specify)
2. What do you do now with your straw? ......leave it on the farm land,..........roof thatching ......other (specify)..................................
3. If proper appliances are available, would you like to use rice husk as substitute for wood/ kerosene in cooking? ....yes...........no
   If no, state reason....................................
4. If proper appliances are available would you like to use rice straw as fuel in cooking? ....yes...............no
   If no, state reasons ....
5. Would you like to use rice husk or straw as fuel for other operations?
   Name the operations..
   If no, state reasons.

E. Collection/Land Use Charges

1. How much work is involved in gathering all the straw into one place? .... man hours
2. Would you consider the following amounts too small, or acceptable, for gathering all your straw in a single location?
   .... Le 50/Acre
   .... Le 100/Acre
   .... Le 150/Acre
   .... other (specify)
3. What is the typical price for labour from your community which could be used to bring straw from farm to town? ....
4. How much labour is involved in gathering all the husk in one place?
   ....man hours.
5. Would you consider the following amounts too small, or acceptable, for gathering all your husk in a single location?
   .... Le 10/sack
   .... Le 20/sack
   .... Le 50/sack
   .... other (specify)

F. Socio-cultural

1. Is there any reason you would not collect, or touch rice husk?
   If yes, specify...
2. Is there any reason you would not collect, or touch rice straw?
   If yes, specify...

3. Do you know of anybody or group of people who will not collect or touch rice husk?.........
4. Is there any reason you would not burn rice husk? If yes, specify ....
5. Is there any reason you would not burn rice straw? If yes, specify..............
6. Do you know of any person or group of persons who would not use rice straw?..............
7. Do you know of any person or group of persons who would not use rice husk?............