BIOMASS PRODUCTION AND ENERGY RELATIONSHIPS

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ABSTRACT

The role the aboveground biomass of forest trees as a source of energy is reviewed. The present energy contribution of about 1.5 quadrillion British thermal units (1.6 × 10^15 kilojoules) can easily be increased to 7 quadrillion British thermal units (7.4 × 10^5 kJ) in the near future.

Fertilization plays a role in producing biomass for energy by (1) making up for nutrient losses on sites where complete biomass harvesting depletes natural nutrition, and (2) improving biomass production on other sites dedicated solely to energy production or to multiple products. In the latter situations the trade-off between energy and other products and the response to fertilizer is strongly influenced by the dimensions reached by individual trees and the end-product utilization standards.

INTRODUCTION

Wood has been a major source of energy since the discovery of fire and worldwide this use accounts for nearly half the annual wood harvest (FAO 1977). Although there are no worldwide data on the quantities involved, a portion of the wood harvested for nonenergy purposes becomes processing residue that may be used for energy and, eventually, even the end product may be used for energy when discarded from its original use. Prior to 1940 wood used for energy accounted for more than half the wood harvest in the United States (Reynolds and Pierson 1942), but by the 1960's this fell to near total disuse, succumbing to cheaper and more convenient fossil fuels. The recent energy crises have stimulated renewed interest in wood for energy.

Recently, the United States has been consuming about 80 quads (84×10^{15} kJ; 1 quad = 10^{15} Btu) of energy per year.[1] By comparison, Tillman (1977) has estimated that in 1976 the pulp and paper industry consumed about 2.2 quads (2.3×10^{15} kJ) and the lumber and plywood industries about 0.2 quads (0.2×10^{15} kJ) of energy from all sources. Based on harvesting and transportation energy consumption data (Koch 1976) it is estimated that these activities use another 0.13 quad (0.14×10^{15} kJ).

The heat of combustion or heating value of wood varies with its chemical content. Resin, tannins, lignin, terpenes, and waxes have a relatively high heat content while carbohydrates have a relatively low heat content. Results of calorimetry experiments indicate that hardwoods contain 8300–8700 Btu per ovendry pound (19 300–20 230 kJ/kg) whereas conifers contain from 9000 to 9700 Btu per dry pound (20 929 to 22 556 kJ/kg). These values are often called the *higher heating value*, since they do not take into account a number of losses that influence the net usable heat, or *lower heating values*. These losses are summarized in Table 1 (Bethel 1977).

Wood has a number of advantages and disadvantages when compared with other fuels for energy. Advantages are as follows:

1. *Burns without toxic emissions*. Only three elements of common fuels have heat value—C, H, and S. Wood and bark, in contrast with fossil fuels, have little or no S content. Thus burning wood does not involve the S compounds that represent

Table 1. Energy losses in burning wood.[a]

1.	Heat required to raise the temperature of water in wood to the boiling point
2.	Heat required to vaporize water in wood
3.	Heat required to separate bound water from the cell walls
4.	In the combustion process, heat required to raise the temperature of the steam to the temperature of the exhaust gases
5.	Heat required to evaporate water formed as a product of the combustion of hydrogen
6.	Heat required to raise the temperature of wood to the combustion temperature
7.	Heat required to raise the temperature of the air used for combustion
8.	Heat loss due to exhaust gases and exhausted unburned combustible materials

[a]Source: Bethel (1977).

1. Throughout this paper be it understood that 1 quad = 1×10^{15} Btu × 1.05435×10^{15} kilojoules. Because quads and British thermal units were determined only to the degrees of precision given, at times the rounded-off number of kilojoules is the same as the number of British Thermal units. Although the kilojoule figure may be somewhat misleading, the author felt that more decimal places (intimating greater precision) would be even more misleading.

the environmentally damaging gaseous components of fossil fuel emissions.

2. *Wide geographic distribution.* Few North American population centers are very far from a potential source of wood.

3. *Wood can be used for energy in solid, liquid, or gaseous form.* Whether or not conversion to liquid or gas is warranted, wood offers flexibility to substitute for a variety of fossil fuel forms.

4. *Wood production is a feasible, large-scale technique for capturing and storing solar energy.* Although photosynthesis is a relatively inefficient solar energy converter, the great size and dispersion of forests makes them effective collectors. Furthermore, unlike annual plants, trees can collect and store solar energy on the stump for relatively long periods thereby enhancing flexibility.

5. *Wood is renewable.*

6. *Wood is flexible in terms of end use.* It is interchangeable for structural, fiber, and energy purposes.

Disadvantages of wood for energy are as follows:

1. *Wood has a low bulk density.* Compared with other fuels a ton of wood occupies more space, making it relatively more expensive and difficult to transport and store.

2. *Wood has a substantial moisture content.* When used for energy, the loss from higher heating value to lower heating value is heavily influenced by moisture content.

3. *Higher heating value is low compared with fossil fuels.* The higher heating value of wood is less than that of coal (8000–14000 Btu/pound [18 600–32 550 kJ/kg]) or petroleum (19900–21000 Btu/pound [46 280–48 830 kJ/kg]).

4. *Geographic dispersion makes collection difficult and expensive.*

5. *Wood emits quantities of particulate matter and water vapor under usual combustion practice. Although nontoxic, these are often viewed as contributing to visual pollution and are often subject to environmental regulation as if they were toxic.*

STATUS AND POTENTIAL OF ENERGY FROM FOREST BIOMASS

The following assessment of physical supplies of forest biomass materials for energy draws from a recent study by a team from the College of Forest Resources at the University of Washington conducted for the Office of Technology Assessment, U.S. Congress (Bethel et al. 1979). In this assessment it should be noted that only the aboveground biomass of forest trees, excluding foliage, is considered and the potential role of tree biomass for energy is examined only to the extent that this use does not deplete wood needed for other purposes. In considering the time between felling and logging, losses during skidding, and the fact that foliage is absent for part of the year on many species, it is unlikely that much foliage would be recoverable. For the study, the United States was divided into the north, south, western pine, Pacific Coast, and Alaska regions. Softwoods and hardwoods were considered separately within each region. Only the national summary data will be presented here.

RESIDUES FROM MANUFACTURING, HARVESTING, AND CULTURAL OPERATIONS

Table 2 summarizes the quantity and use of residues produced by manufacturing, harvesting, and cultural operations and shows that these sources presently contribute about 1.3 quads (1.4×10^{15} kJ) or less than 2% of current U.S. energy

Table 2. Energy production and potential from manufacturing, harvesting, and silvicultural operation residues.

Residue source	Total production $\times 10^6$ ODT	Percent used as: Nonfuel	Fuel	Unused	Energy $\times 10^{15}$ BTU: Current	Potential addition
Manufacturing						
Primary						
Bark	17.7	14	69	18	0.219	0.052
Green chip	35.2	85	11	4	0.065	0.026
Other green	13.9	33	43	24	0.104	0.056
Dry	12.2	55	26	9	0.077	0.015
Total	79.0	68	23	9	0.465	0.149
Secondary	10.3	65	20	15	0.050	0.026
Spent pulp liquor	64.8				0.797	
Total manufacturing					1.312	0.175
Harvesting	84.1	0	0	100	0	1.3
Silviculture	47.0	0	0	100	0	0.7
Land clearing	65.0	0	0	100	0	1.0
Total					1.312	3.2

consumption. This could be increased to 4.5 quads (4.7×10^{15} kJ) through the use of currently unused residues.

MANUFACTURING RESIDUES

Primary manufacturing includes the lumber, plywood, pulp, cooperage, pole, piling, post, round mine timber, and other industries. The volume of softwood and hardwood log input into each of these categories by region (USDA Forest Service 1978) was used as the starting point in the analysis. Difficulties were encountered in using USDA Forest Service estimates of residue production from these sources since the recent statistical summary (USDA 1978) presents only the quantity of unused woody residues classified by size as "coarse" or "fine." These size classifications are inadequate for energy studies since they mix residues of different moisture contents. Also, the statistics ignore the production of bark residue. Since a complete breakdown of total residue production was needed according to residue type, moisture content, and use, individual industry materials balance diagrams such as shown in Figure 1 were developed for hardwood and softwood conversion in each region. The diagrams portray, in terms of both volume and weight, estimates of the production of residues and end product at each stage of manufacture, moisture content, and how much of each form of residue is presently being used for fuel, for other uses, or is unused and therefore potentially available for fuel.

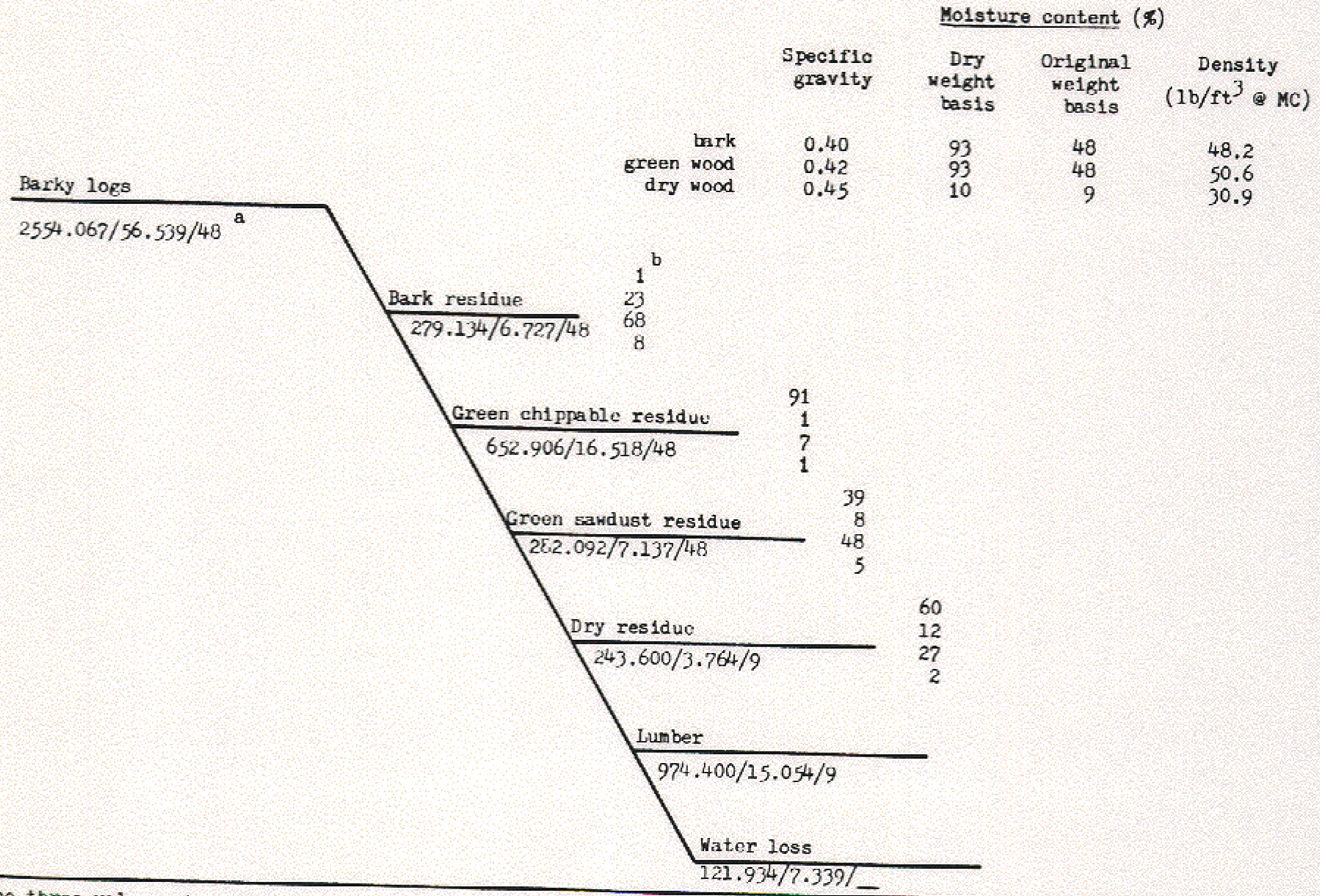
Secondary manufacturing includes industries such as millwork, prefabricated housing, and furniture, which convert raw material obtained from primary manufacturing industries into finished goods. Residue produced by these industries generally is relatively dry. Unfortunately, statistical information on raw material inputs to these industries and residue production is lacking and studies on the amount and disposition of residues from these industries have been few and sporadic. The estimate shown in Table 2 is based on extrapolation from these few studies.

Spent pulp liquor is another major forest industry residue. The spent liquor contains roughly half of the input wood tonnage. Tillman (1977) recently estimated that about 0.8 quad (0.8×10^{15} kJ) of energy are recovered from the spent pulp liquor. Energy obtained by this industry from bark and reject chips is included in the total for primary manufacturing.

HARVESTING RESIDUES

United States Forest Service statistics on logging residues (USDA 1978) underestimate the total quantity generated since

Figure 1. Materials balance diagram for Pacific Coast softwood lumber



[a] The three values at each point in the balance are: cubic volume (million cubic feet), weight (million tons at MC), moisture content.

[b] The four values at the end of each residue component are the percent used for pulp and board industry furnish, other uses, fuel or unused.

they reflect only unused wood material from growing stock trees, i.e., commercial species trees that are at least 5.0 in. (12.7 cm) dbh and are not classified as rough or rotten trees. Furthermore, the logging residue reported represents only the unused portion of these trees between a 1-ft (30-cm) stump and a 4-in. (10-cm) top. Consequently, bark, residues from non-growing stock trees on logged-over areas, tops above the 4-in. (10-cm) limit, branches, and stumps all are ignored. In local studies of logging residues, various individual authors found inconsistencies in classifying logging residues into size classes, making it difficult to compare and combine results. Furthermore, there are inconsistencies in classification of non-growing stock logging residues. If the tree is cut, there is no question that the unused parts constitute logging residue; but what if a nongrowing stock tree or a cull tree is left standing? Some studies have included these uncut trees on logged areas as logging residue (the logger simply avoided felling them) while others have not included them.

Estimates of logging residues including all sizes, classes, bark, and nongrowing stock were obtained by comparing the statistics (USDA 1978) with local but more detailed studies and developing adjustment factors for the components missing in the USDA Forest Service statistics. It is estimated that approximately 84 million ODT (76 million metric tons) or 1.3 quad (1.4×10^{15} kJ) of logging residue is potentially available for energy.

RESIDUES FROM SILVICULTURAL OPERATIONS

Residues from thinnings, weedings, timber stand improvement (TSI), and so forth were very difficult to quantify as there are few data on the areal extent of these activities, to say nothing of the quantity of residue generated. A recent survey (DeBell et al. 1977), however, revealed the percentage of industry-owned lands receiving various treatments and provided a starting point for a crude estimate. These percentages, applied to statistics on industry landholdings, suggest that TSI, species conversion, and weed control were performed on about 1.7 million acres (0.7 million ha) annually and that precommercial and commercial thinnings were annually conducted on another 1.8 million acres (0.7 million ha). An average residue yield of 17 ODT per acre (38 t/ha) for the TSI, species conversion, and weed control and 10 ODT per acre (23 t/ha) for the thinnings was assumed.

These residue yield values were the midpoints in a range of residue estimates derived from a variety of published reports and conversations with foresters. Combining these yields with the treatment area estimates suggests that about 47 million ODT (43 million t) of cultural residues are produced annually. This represents an energy potential of about 0.7 quad (0.7×10^{15} kJ). Recently, Welch (1978) published results of a survey in five southeastern states indicating that residues from cultural operations, excluding commercial thinnings, were 94 million ft^3 (2.7 million m^3). This translates into about 1.4 million ODT (1.3 million t) or about 0.02 quad (0.02×10^{15} kJ).

RESIDUES FROM LAND CLEARING

Residues generated from clearing forest land for farming, housing, roads, powerlines, and other uses represent another source of biomass for energy. This may be a useful short-term supplement to energy supplies in some locations but it may occur on an intermittent basis. Detailed statistics on the area and quantity of biomass involved are just beginning to emerge for some locales. For example, Bones (1977) presented data suggesting that land-clearing operations in New England produce about 35 ODT of residue per acre (78 t/ha). Data presented by Welch (1978) for five southern states suggest that land-clearing operations create about 30 ODT of residue per acre (67 t/ha).

For the United States, I have estimated that approximately 1.7 million acres (0.7 million ha) of forest land are being cleared annually. This estimate is based on rates reported in forest survey reports for individual states. Using regional biomass per acre values estimated from the OTA study (Bethel et al. 1979), this represents about 65 million ODT (59 million t) of residue per year which translates into an energy potential of 1 quad (1.055×10^{15} kJ).

BIOMASS FROM STANDING TIMBER

In addition to utilizing biomass residues from manufacturing and forest culture practices for energy, there are opportunities for directly harvesting timber for that purpose and applying practices that increase the total physical supply of forest biomass for energy as well as structural and fiber products. It is in this domain that fertilization can play a role.

CURRENT HARVEST FOR ENERGY

Harvesting of timber for fuelwood in 1976 amounted to 10.2 million ODT (9.3 million t), which translates into 0.260 quad (0.274×10^{15} kJ). The timber has been harvested through conventional firewood cutting and the statistics may underestimate the real level of this activity. Consumption of charcoal is about 0.7 million ODT (0.635 million t) representing about 0.015 quads (0.016×10^{15} kJ). Fuelwood and charcoal figures probably reflect recreational and aesthetic pursuits more than use for primary heating and cooking. The picture is changing rapidly, however, and wood undoubtedly will assume a greater role as a primary or supplementary source for heating and cooking in many homes.

POTENTIAL FOR EXPANDED HARVEST OF BIOMASS FOR ENERGY

In assessing the potential for expanded use of forest biomass for energy, it must be recognized that any component of any tree can be used for the purpose. Therefore, making a meaningful judgment on an expanded role of U.S. forests for energy should involve data on the inventory and growth of biomass of trees, categorized by components. Unfortunately, the forest survey, which presents periodic regional and national assessments of the physical timber supply, is inadequate because of assumptions concerning utilization standards and thresholds of commerciality.

When the forest survey was initiated, it became a standard practice to characterize the inventory and production of a stand or a tree in terms of its sawtimber content. This involved assumptions concerning lumber manufacturing practices and the sizes, species, and qualities of timber that would be used. The possibility that the tree, stand, or log would yield a variety of products was ignored. These assumptions affect which trees are tallied and how much of each is tallied. Both the final inventory and its growth are then based on measures that rest on the assumptions. Use of the assumptions results in a survey that ignores substantial fractions of biomass and biomass growth that could be useful for energy or other products.

Excluded are quantities on land areas regarded as noncommercial, trees that for one reason or another are regarded as noncommercial, and components of commercial trees that do not meet the conventional sawlog-oriented utilization criteria used in the survey. As an example of the magnitude of difference between the total tree aboveground biomass on a site and the portion conventionally inventoried, Bradley and Stephens (1978) reported on a comparison in Vermont of three conventional inventories conducted on a tract of land with the actual yield obtained through a clearcut, whole-tree chipping operation. The operation removed 3–4.5 times the tonnage predicted by the preharvest surveys.

Another deficiency of the forest survey is its lack of qualitative information to complement the quantitative information. A tree on a site is categorized as a growing stock tree as long as it meets growing stock tree definition. There is no qualitative indication as to whether the tree is appropriate for the site. Stands are rarely evaluated in terms of over- and understocking with desirable trees nor is information available on the treatment they should receive and the fraction of the total stand that should be treated. Information on the condition of lands combined with quantitative data are needed for planning forestry needs and the potential scope of various programs.

For example, an estimate of the area and biomass of low-grade junk stands that should be converted to other species is desirable for assessing possible energy programs but relatively little information is available to accomplish this. A crude but undoubtedly conservative estimate can be made based on the survey categories of rough, rotten, and salvable dead trees. The volumes reported in these categories were converted to biomass using average factors developed by Wahlgren and Ellis (1978). The factors were derived from published biomass research and can be applied to conventional survey data to crudely convert it biomass. The estimate for the United States in these tree categories is 2444 million ODT (2219 million t).

It was also estimated that low-quality hardwood and brush occupying former conifer sites in the West amounts to another 301 million ODT (273 million t) of biomass. Combined, these sources represent a 40-quad (42×10^{15} kJ) reservoir of readily available biomass unsuited for almost any use except energy.

The inventory of biomass on all commercial forest lands was estimated in two ways. One approach applied the multipliers derived by Wahlgren and Ellis (1978) to convert forest survey volumes to a biomass basis. These factors were applied to the most recent forest survey statistics (USDA 1978). The second approach relied on applying individual tree biomass component regression equations to stand table data for all live trees, growing and nongrowing stock, in the forest survey (USDA 1978).

Equations were restricted to those that used diameter at breast height as the independent variable and of those that met this requirement a representative softwood and hardwood was chosen for each region. Specific gravity adjustments were made when it was apparent that the equation species chosen differed greatly from the typical softwood or hardwood in a region. The estimates by these two methods, respectively, were 24.2 and 25.4 billion ODT (22.0 and 23.0 billion t) of aboveground tree biomass on commercial forest land. Dividing by the acreage of commercial forest land, this is an average of about 50 ODT per acre (112 t/ha). Note that this is an overall average for all levels of stocking, included nonstocked commercial forest land.

The biomass on noncommercial forest land was more difficult to estimate since the survey presents only the area of these lands. After deducting various lands reserved from harvesting, biomass was estimated by assuming an 80-yr rotation and an average annual biomass increment of 0.22 ODT/acre (0.49 t/ha) per yr on lands regarded as noncommercial because of low productivity and 0.78 ODT/acre (1.75 t/ha) per yr on lands regarded as noncommercial because of other factors, principally access.

Values were based on assumptions of cubic foot site productivity of 10 and 35 ft^3/acre (0.7 and 2.4 m^3/ha) per yr, respectively. Values were adjusted for other tree components and converted to weight. The calculations led to an estimate of about 5.1 billion ODT (4.6 billion t) of biomass on noncommercial forest lands. Combining the estimates on commercial and noncommercial forest lands, the aboveground biomass on all forest lands is estimated to be in the range of 29.3–30.5 billion ODT (26.6–27.7 billion t).

In assessing biomass growth on commercial forest lands, the assumption was made that the percentage of growth rate of all biomass components was essentially the same as the bole. On the basis of this assumption, gross annual aboveground biomass growth was estimated as 570 million ODT (517 million t) on commercial forest lands or about 1.2 ODT/acre (2.76/ha) per yr. This may be a conservative estimate since the basis for bole growth is normal yield tables, which are often conservative because they incorporate utilization assumptions. Furthermore, in a comparison of the growth of Douglas-fir control plots in the University of Washington, College of Forest Resources, Regional Forest Nutrition Research Project (RFNRP) with estimates from McAndle et al. (1949), it was found that the normal yield tables consistently underestimated actual growth. The average difference was about 40%.

In parts of the Rocky Mountains on low-site lands, actually measured growth is often two to three times the value that would be assigned on the basis of normal yield tables. In many cases the difference would reclassify lands from noncommercial to commercial forest status. In considering these factors, the energy study team concluded that the actual biomass growth figure may be as much as double the preceding estimate and is in the range of 570–1140 million ODT (517–1034 million t) per yr (1.2–2.4 ODT/acre [2.7–5.4 t/ha] per yr).

It was also recognized that the actual tree biomass growth may be well below the site potential. Based on forest survey measurements comparing the ratio of growth to site capacity, potential growth of all commercial forest lands, under conditions of proper stocking with the best species adapted to the site, may be on the order of 1110–2220 million ODT (1008–2016 t) per yr (2.3–4.6 ODT/acre [5.2–10.4 t/ha] per yr).

Further increases in this potential may be possible through practices such as fertilization and irrigation that boost site capacity, or genetic manipulations producing better adapted, more productive trees. Considering these practices, the theoretical potential biomass growth capability of commercial forest lands may be in the range of 1450–2900 million ODT (1316–2632 t) per yr (3.0–5.9 ODT/acre [6.7–13.2 t/ha] per yr). Although it is unlikely that these high levels are economically, environmentally, or politically achievable, these crude theoretical estimates do indicate that there may be substantial opportunity to increase the rate of forest production and increase the role of forests for both energy and materials use.

To put these growth estimates in perspective, recent levels of roundwood harvest have been somewhat less than 200 million ODT (182 million t) per yr (CORRIM 1976). Adjusting for bark and including the estimate of logging residues in Table 2, current harvesting operations remove approximately 300 million ODT (272 million t) per yr. The difference between this level of use and the estimate of current biomass growth, 570–1140 million ODT (517–1034 million t) per yr is 4–13 quads (4–14 × 10^{15} kJ). This is a very crude estimate and work is desperately needed in improving the survey so that more refined estimates can be made.

ROLE OF FERTILIZATION IN PRODUCING ENERGY FROM BIOMASS

Since any biomass component can be used for energy we may be witnessing the beginning of an era of much greater use of whole-tree harvesting methods. In some cases use of these techniques may deplete natural nutrient stocks, thus requiring the use of fertilizer supplements for site maintenance.

The use of fertilizer to improve site production capacity was mentioned in the preceding section as a way of increasing the total physical supply of biomass. In some situations fertilizer may be applied solely for accelerating biomass production for energy purposes. In extreme form, this is the energy farm concept. The biomass response to fertilizer would be evaluated in terms of increased energy production.

In the situation that is common today, fertilizer is applied to stimulate production for a variety of end products (lumber, plywood, fiber, and the like) and energy could be considered as a competing alternative in the integrated utilization concept. Use for energy of some or all of the growth response to fertilizer must be evaluated in the context of the other possible uses. Even when part or all of a stand, tree, or log is dedicated to some nonenergy use, however, energy remains in the picture since it is a use for logging and manufacturing residues.

In integrated product systems, energy and fertilizer response can have some interesting interactions for it is possible, especially when logs are produced for lumber manufacture, that the fertilizer response may become mostly residue that could be used for energy. In lumber manufacture this occurs because of the nature of U.S. softwood lumber standards, where lumber sizes take discrete jumps in length, width, and thickness. To see the effect of this, consider a simple case in which small logs are gang sawn into 2- by 4- and 2- by 6-in. (5- by 10- and 5- by 15-cm) boards in lengths of 8 ft (2.4 m). Table 3 indicates the softwood lumber standards for 2-in. (5-cm) thickness and 4-and 6-in. (10- and 15-cm) widths.

Table 3 also shows data taken from Williston (1976) used to estimate the target dimension for sawing. By finding the smallest log that a mill could process into lumber under these conditions and gradually increasing its diameter, changes in the mixed lumber and residue production can be noted. The bottom of Figure 2 portrays the results in terms of cubic feet and shows how a large change in diameter is often necessary before any change in lumber production occurs. In this case it was assumed that the mill objective is to maximize lumber recovery.

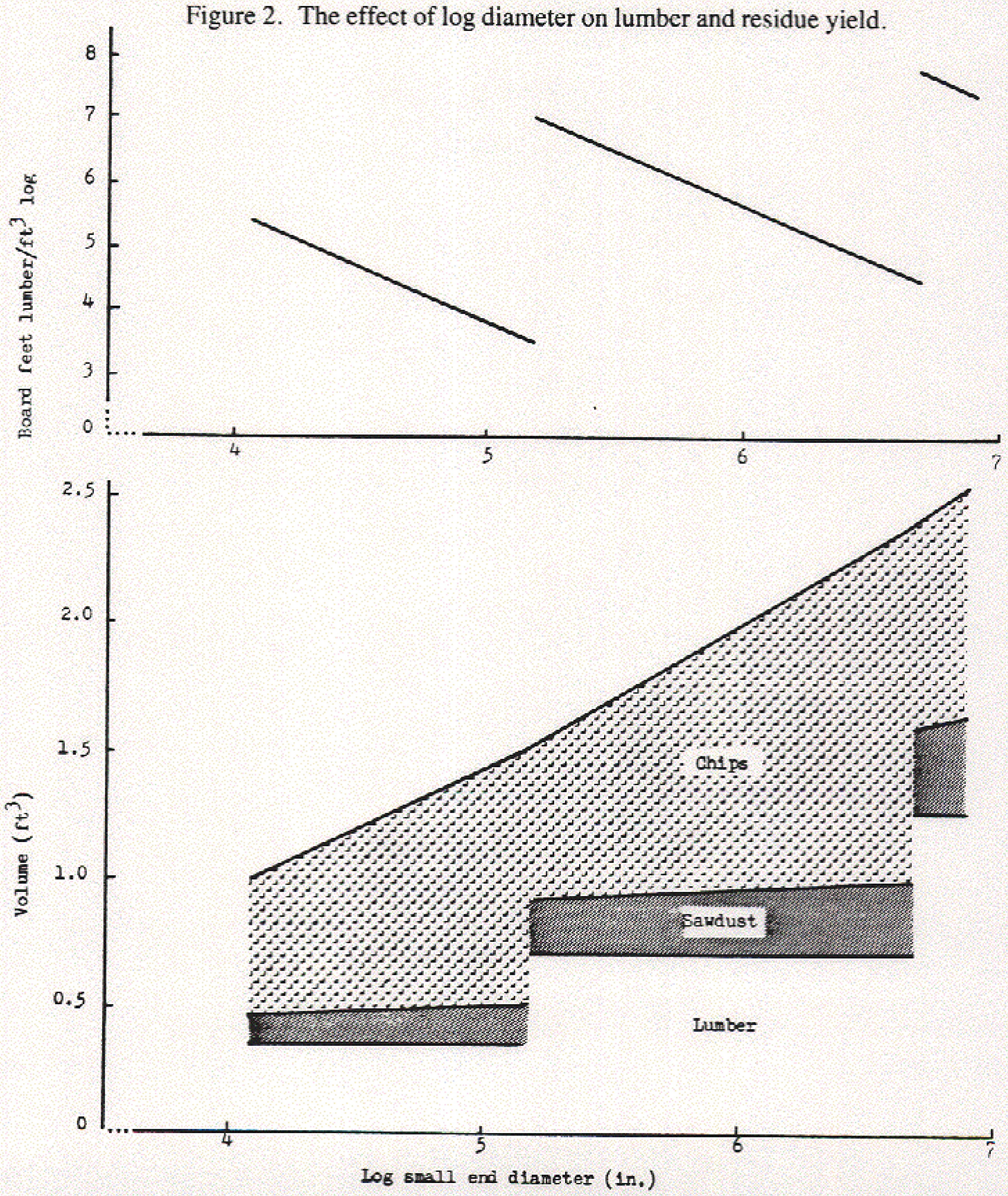
The top of Figure 2 portrays the ratio of board feet of lumber to cubic feet of log input known as the lumber recovery ratio. These graphs show that if the log did not change from 4.1 in. (10.4 cm) to about 5.2 in. (13.2 cm) or from about 5.2 in. (13.2 cm) to 6.7 in. (17.0 cm), then all that was gained was residue. The changes in log size could be due to natural growth or could be accelerated by fertilizer. The size change must be sufficient to allow the mill to produce larger boards meeting

Table 3. Summary of production parameters for a hypothetical sawmill producing 2 × 4 and 2 × 6 lumber.

		Thickness (in.)	Width (in.)	Width (in.)
1	U.S. Lumber Standard, nominal	2	4	6
2	U.S. Lumber Standard, surfaced green	1 9/16 = 1.562	3 9/16 = 3.562	5 5/8 = 5.625
3	U.S. Lumber Standard, surfaced dry	1 1/2 = 1.500	3 1/2 = 3.500	5 1/2 = 5.500
4	Shrinkage allowance, 3%	0.045	0.105	0.165
5	Planning allowance	0.140[a]	0.035[b]	0.035[b]
6	Sawing variation allowance	0.066[a]	0.060[b]	0.060[b]
7	Target dimension, 3 + 4 + 5 + 6	1.729	3.700	5.760

[a]Sash gang headrig, data from Williston (1976, p.422). [b]Over or under battery type circle saw edger, data from Williston (1976, p. 422).
Saw kerf: headrig = 3/16 in. = 0.190 in., edger = 1/8 in. = 0.125 in., trimmer = 1/8 in. = 0.125 in.

Figure 2. The effect of log diameter on lumber and residue yield.



the lumber standards or to produce more boards, or the entire change becomes manufacturing residue.

The other side of the coin occurs in the tree since a size change, due to fertilizer for example, may increase the usable length for lumber as well as alter log diameters. For example, in analyzing a 14.4-in. (36.6 cm) dbh, 94-ft- (28.7 m-)tall tree for 8-, 10-, 12-, 14-, and 16-ft (2.4-, 3.0-, 3.7-, 4.3-, and 4.9-in.) log lengths with a 3-in. (7.6 cm) trim allowance on each end, three 16-ft (4.9 m) logs and one 12-ft (3.7 m) log were found to be the optimum combination. When this tree had grown to 15.0 in. (38.1 cm) dbh and 96 ft (29.3 m) in height, however, four 16-ft (4.9-m) logs were best. Although the combined sawlog length increased by only 6%, the lumber volume increased by 14% and this occurred while the total number of boards decreased by one.

Figure 3 illustrates the effect of changing tree diameter on lumber recovery in trees ranging from 14 to 17 in. (35.6 to 43.2 cm) dbh. In this example, nominal 2-in.-thick (5-cm) lumber was produced under the conditions in the preceding example except that all lumber widths were allowed. Lengths were 8–16 ft (2.4–4.9 m) in 2-ft (0.6-m) intervals plus a 3-in. (7.6 cm) log trim on each end. The effect observed earlier in individual logs is also apparent when tree size changes. Lumber recovery generally increases with tree size but the transition is not smooth. For example, notice the sudden jump from 14.8 to 15.0 in. (37.6 to 38.1 cm) and the slight drop from 15 to 15.2 in. (38.1 to 38.6 cm). For any diameter, the specific location of points in this graph would change with tree height and with the utilization assumptions. These results were obtained from a utilization systems model that examines trees with a bucking optimization routine and a sawing model that indicates the optimum strategy for live sawing logs into lumber (Briggs 1978).

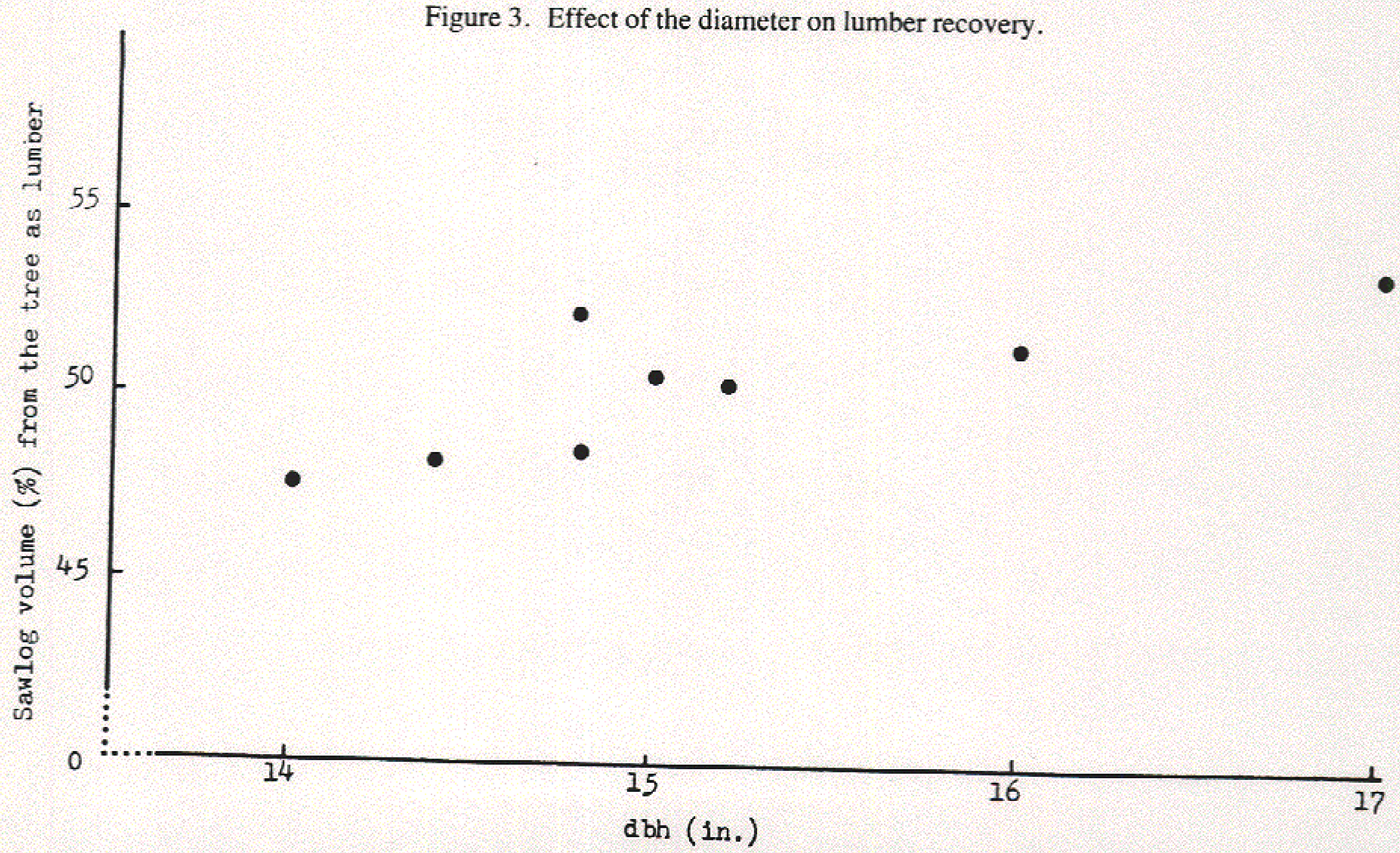
Evaluating fertilization response in terms of end-product utilization criteria in an integrated manufacturing setting is a complex problem and the result depends on the initial and final dimensions achieved by the tree and the utilization parameters. These trade-offs may have important implications in evaluating the timing of fertilization and determining how to best use the biomass response.

SUMMARY AND CONCLUSIONS

On a biomass basis, U.S. forest lands are today capable of providing significant energy input. In the energy study (Bethel et al. 1979), it was concluded that the total contribution of wood to energy supply easily could be increased to at least 7 quads (7×10^{15} kJ) annually in the very near future. This represents about 12% of recent levels of national energy use and represents about 2.5 times the contribution from Iran prior to the revolution. By comparison, Kalish (1979) reported that wood contributes 9% of the energy consumed in Sweden and 15% in Finland. An increase in the United States would be achieved through use of currently unused manufacturing, logging, and cultural residues; by tapping the huge reservoir of junk timber biomass; and by tapping surplus biomass growth exceeding needs for conventional products.

In the long run it was concluded that a commitment toward improving the stocking and growth of tree biomass would allow the nation to meet material needs for structural and fiber wood and produce a surplus to allow increased use of wood for

Figure 3. Effect of the diameter on lumber recovery.



energy. Fertilization will play a role in increasing the supply of wood and in maintaining site productivity. The amount of biomass produced in response to fertilization that may become energy involves a complex interaction between individual tree characteristics and the utilization system.

It is apparent that the national forest survey should be redesigned to provide a census of inventory and growth on a whole stem basis not obscured by utilization assumptions. The deficiencies noted in the forest survey are a concern not only to those pursuing energy studies. They were noted as inhibiting factors by the Committee on Renewable Resources for Industrial Materials of the National Academy of Sciences (CORRIM 1976). The survey should be expanded to include a qualitative assessment of the condition of forests to complement the quantitative data. With this background information, scientists and planners can apply their own utilization standards.

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