ENERGY RELATIONS IN FOREST FERTILIZATION

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ABSTRACT

It is a business of the forest industry to collect and store solar energy in the form of wood. One alternative is to use little if any fossil fuel energy, but rely on human and animal muscle power and on natural fertilizers to increase the efficiency of solar energy captured by trees. Where this is the case, forestry may be considered fossil-fuel-energy efficient but productively inefficient. Another alternative is to substitute engine power, pesticides, and synthetic fertilizers for muscle power and natural fertilizers. A cost in fossil fuel energy is exacted, but the benefit derived is a higher productivity level. The United States forest industry has developed along the latter course.

INTRODUCTION

The total energy consumed in the United States is estimated at 83 quads (83 x 10^{15} Btu), with an annual growth rate of 3% (Blouin and Davis 1975). The 83 quads represent one-third of the total energy consumed in the world (Stickler et al. 1975). The U.S. forest industry requires 2.7 quads, which is equivalent to 3.3% of the U.S. total. Wood wastes provide approximately half the forest industry requirements (Gessel, pers. commun.). The fertilizer industry requires 0.56 quad to produce, store, distribute, and apply some 50 million tons of N, P, and K products, which is 0.7% of the total U.S. energy consumption (Blouin and Davis 1975).

Only a small part of the sun's available energy reaches the earth for conversion by trees to chemical energy (Stickler et al. 1975). An even smaller part trickles through to produce a two-by-four, a sheet of plywood, a newspaper, or a milk carton. Compared with other industries, however, growing of wood is one of the most efficient systems in which fossil fuel energy can be expended to increase photosynthetic efficiency and thus wood production.

Burks (1978) estimated energy requirements for silvicultural operations under different management levels on a Douglas-fir stand, up to thinning, on site II with site preparation, planting, and fire protection. The estimated energy return per unit of input was 537:1. Under intensive management (including the above-mentioned procedures plus aerial spraying, stocking control, and fertilization in a 45-yr rotation), the ratio was 31:1 (Burks 1978). Smith and Johnson (1977) estimated a ratio of 157:1 under intensive management including 100 lb N/acre as urea in a 30-yr rotation.

Energy efficiency ratios for some agricultural crops are: corn with 200 lb N/acre, 7:1; and grain sorghum with 150 lb N/acre, 4:1. Other crops such as cauliflower require over 8 cal of input to achieve 1 cal in the final product (White 1978).

It is now well established both in field research results and in operational forestry that N fertilization is a practical, economical means for increasing yields of Douglas-fir forests in western Washington and Oregon. The question of energy tradeoffs is less clear, particularly as they relate to N sources.

NITROGEN PRODUCTION

Nitrogen is one of the light elements, with an atomic number of 7 and an atomic weight of 14. Free N is abundant in the atmosphere, of which N makes up approximately four-fifths by volume. Unfortunately, trees cannot utilize atmospheric N; they must have a supply of combined or fixed N for growth. Some processes in nature, such as lightning and microorganisms, can utilize N directly and make a major contribution to wood production; however the addition of fertilizer N is needed for optimum growth.

Three industrial processes have been developed during the past 180 yr for fixation of atmospheric N. They are (1) the electric arc process for production of nitric acid, (2) the process for manufacture of calcium cyanamide, and (3) the process for reacting H with atmospheric N to form ammonia. Nearly all the N produced in the United States is made from synthetic ammonia by the last process, known as the *Haber-Bosch process*, using natural gas for both fuel and feedstock.

Approximately 38,000–40,000 ft^3 of natural gas is required to produce a ton of ammonia. Forty percent of the gas is burned as fuel and the remainder is used as feedstock to produce N. Of the energy, 99% is supplied by natural gas and 1% by electricity (Davis and Blouin 1977). Synthesis of ammonia is represented by the equation:

$$3\ H_2 + N_2 \rightarrow 2\ NH_3 \text{ (catalytic)}$$

Ammonia synthesis is carried out in the presence of an iron catalyst at 3500 psig (pounds of pressure per square inch gauge pressure) and 950°F. Synthesis of ammonia is a relatively simple process compared with preparation of the raw materials.

There are three processes for H production. They are (1) steam reforming of natural gas or naphtha, (2) partial oxidation of fuel oil, and (3) gasification of coal. Most of the ammonia plants being built today are designed to produce synthesis gas by steam reforming of natural gas. The reactions are represented by the equations:

$$CH_4 + H_2O \rightarrow CO + 3\,H_2 \text{ (catalyst)}$$
$$CO + H_2O \quad H_2 + CO_2 \text{ (catalyst)}$$

The objective is to reduce H from natural gas to free H, and to crack the steam feed to free H by oxidizing the C in natural gas to carbon dioxide. The reactions are carried out a 300–400 psig and 1500°F in the presence of a Ni catalyst.

Total estimated energy consumption for production of anhydrous ammonia via the various feedstocks is given in Table 1. The data indicate that the processes require about the same amount of energy except for gasification of coal, which requires about 40% more energy.

The data in Table 1 are estimates made by Blouin and Davis (1975) that represent a theoretical maximum production efficiency. It should also be noted that a low heating value was used for feedstocks. The Fertilizer Institute (1979) released an energy use survey based on data received from member producers for calendar year 1978. The data in Table 2 represent average energy consumption in current operating plants of all sizes and technologies. Energy requirements are substantially greater in operating plants than the theoretical maximum efficiency.

Table 1. Estimated energy (Btu × 10^6) consumed in production of anhydrous ammonia.[a]

Procedure	Normal units/ton NH_3	Energy consumed[b] per ton NH_3	Energy consumed[b] per ton N
Steam reforming			
Natural gas (900 Btu/ft^3)[c]	38 ft^3 × 10^3	34.2	41.5
Electricity	20 kW·h	0.2	0.3
Total		34.4	41.8
Naphtha reforming			
Naphtha (19,000 Btu/lb)[c]	0.89 ton	33.8	41.0
Electricity	25 kW·h	0.3	0.4
Total		34.1	41.1
Heavy oil--partial oxidation			
Fuel oil (17,500 Btu/lb)[c]	0.98 ton	34.3	41.6
Electricity	30 kW·h	0.3	0.4
Total		34.6	42.0
Coal gasification			
Coal (11,400 Btu/lb)[c]	2.0 ton	45.6	55.3
Electricity	235 kW·h	2.4	2.9
Total		48.0	58.2

[a]Blouin and Davis (1975). [b]Including estimated energy required to produce and deliver raw materials. [c]Low heating value (LHV).

Table 2. Average energy consumption in anhydrous ammonia production (× 10^6 Btu/ton).

Source	Per ton NH_3	Per ton N
TFI survey[a]		
Reciprocating plants	38.0	46.3
Centrifugal plants	41.7	50.8
TVA[b]		
Maximum efficiency	34.4	41.8

[a]TFI = The Fertilizer Institute. [b]TVA = Tennessee Valley Authority.

Urea is produced by reacting ammonia and carbon dioxide at high temperature and pressure. The carbon dioxide is a by-product from natural gas. Urea melt is produced and converted to solid granules or prills, or to solutions. Estimates of energy required to convert ammonia to urea range from 3 to 7 million Btu/ton N.

Ammonium nitrate is produced by oxidizing ammonia to nitric acid, then neutralizing the nitric acid with additional ammonia. Since the nitric acid reaction is exothermic, there is a gain in energy. The ammonium nitrate melt is converted to solid prills or granules, or to solutions. Estimates of energy required to convert ammonia to ammonium nitrate range from 0.9 to 8 million Btu/ton N (Table 3).

Estimated energy requirements for production of urea and ammonium nitrate suggest there may be only a slight advan-

Table 3. Average energy consumption in N protection (× 10^6 Btu/ton).

Source	TFI[a]	TVA[b]
Ammonia	49.9	42
Urea		
granular	3.3	7
solution	3.8	3
Ammonium nitrate		
granular	3.0	8
solution	0.9	4

[a]Fertilizer Institute (1979). [b]Davis and Blouin (1977).

tage, if any, for solid urea over solid ammonium nitrate, and perhaps only a small advantage in favor of solutions over solids.

TRANSPORTATION

Estimated fuel consumption required to move 1000 gross tons a distance of 1 mi is 2.31 gal of diesel fuel (Uggerslev, pers. commun. 1979). A gross ton includes the car weight of 30 tons and contents of 100 tons. One gallon of diesel fuel will move 433 gross tons or 3.33 loaded cars 1 mi. If the average distance hauled is 800 mi, 480 gal of diesel is required to deliver 100 tons of urea and return the car. Thus the consumption per ton of urea is 4.8 gal. Assuming 1 gal of diesel fuel produces 140,000 Btu and a ton or urea contains 920 lb of N, it requires 730 Btu to transport 1 lb of N 800 mi and return the car.

DISTRIBUTION/APPLICATION

The estimated fuel consumption required to truck fertilizer an average of 20 mi from railhead to heliport ranges from 0.40 to 0.65 gal of diesel fuel per ton of urea. Another 0.60–0.75 gal of gasoline per ton of urea is consumed by support equipment. Finally, application of urea by helicopter requires another 2.5–3.40 gal of jet fuel per ton of urea (Table 4).

Table 4. Estimated fuel required to truck urea 20 mi from railhead to heliport and apply it.

Equipment	Fuel	Gas/ ton urea
Helicopter[a]	Aviation gas	2.75
Trucking	Diesel	0.65
Support	Gasoline	0.60
Total		4.00
Helicopter[b]	Jet fuel	2.50
Trucking	Diesel	0.65
Support	Gasoline	0.60
Total		3.75
Helicopter[c]	Jet fuel	3.40
Trucking	Diesel	0.40
Support	Gasoline	0.75
Total		4.55

[a]Small Hiller 12-E, payload 800 lb, bulk system. (Private commun., Western Helicopters, Newberg, Oreg., and Reforestation Services, Salem, Oreg.). [b]Hiller 12-E-J3 (turbo), payload 1100 lb, bulk system. (Private commun., see [a].) [c]Bell 205-A-1, payload 3300 lb, 3000-lb bags. (Private commun. Helijet Corp., Eugene, Oreg.).

Estimating the energy produced by diesel fuel at 140,000 Btu/gal, by gasoline at 125,000 Btu/gal, and by jet fuel at 135,000 Btu/gal (Table 5), the energy required to apply a pound of N as urea is 600 Btu. Results from the Regional Forest Nutrition Research Project (RFNRP; Univ. Washington 1979) show that 200 lb N/acre applied as urea on unthinned, 25- to 55-yr-old Douglas-fir stands increased wood volume by approximately 400 ft^3/acre.

Table 5. Energy (Btu) available from various fuels.[a]

Fuel	Btu/gal
Kerosene	135,000
No. 1 fuel oil	140,000
No. 2 fuel oil	140,000
No. 5 fuel oil	150,000
No. 6 fuel oil	151,000
Gasoline	125,000

[a]Source: Husky Oil Co. and Union Oil Co.

ENERGY RELATIONS

Using the RFNRP response data and energy requirements estimated for N, an energy balance was calculated based on application of 200 lb N/acre and an added yield of 400 ft^3 of wood. The calculation shows that 29,300 Btu of energy are required to produce, transport, and apply a pound of N on a typical forest site. Energy required for harvesting the added volume was estimated at 16,000 Btu/ft^3. Thus, with an input of 29,300 Btu, an output of 413,000–481,000 Btu was realized. The corresponding input-output ratio ranged from 1:14 to 1:16 (Table 6). The energy ratios estimated here are somewhat higher than estimates of Miller and Fight (1979) and Smith and

Table 6. Energy balance with 200 lb N/acre applied as urea on Douglas-fir with an added yield of 400 ft^3 of wood.

	Nitrogen (Btu/lb)		Wood (Btu/2 ft^3)
Production	28,000	Yield	430,000–498,000
Transportation	700		
Application	600	Harvest	(16,800)
Total	29,300		413,000–481,000
Ratio: 1:4 to 1:16			

Johnson (1977) of 1:11 and 1:12, but in view of the obvious inaccuracies in any estimate, they are in general agreement (Table 7).

Table 7. Energy units (representative values).

1 Btu (British thermal unit) = quantity of heat required to raise temperature of 1 lb water 1°F
1 kcal = quantity of heat required to raise temperature of 1000 g of water 1°C
1 therm = 100,000 Btu
1 Btu = 0.252 kcal
1 Kw·h = 3412 Btu (10,000 Btu generate 1 kW·h of electricity)
1 ft^3 gas (methane) = 1012 Btu
1 ft^3 gas (methane) weighs 0.0425 lb
40,000 ft^3 gas weighs 1700 lb
1 lb NH_3 = 9667 Btu
1 ton NH_3 = 19.3×10^6 Btu
40,000 ft^3 gas = 40.5×10^6 Btu
1 ton coal = 28×10^6 Btu
1 gal no. 4 fuel oil = 144,000 Btu
267.5 gal no. 4 fuel oil weighs 1 ton
1 ton no. 4 fuel oil = 38.5×10^6 Btu
1 barrel (U.S.) = 42 U.S. gal
1 barrel crude oil = 5.8×10^6 Btu

Source: W. C. White, vice-president, member services, The Fertilizer Institute.

CONCLUSIONS

(1) The long-term trend in forest industry is to become less energy efficient, but more productive. (2) Ratio of energy input as fertilizer to output in terms of added wood volume is favorable. (3) Existing relations are viable only as long as the investment in energy inputs provides satisfactory economic returns.

LITERATURE CITED

Blouin, G. M., and C. H. Davis.
1975. Energy requirements for the production and distribution of chemical fertilizers in the United States. TVA Bull. X294, p. 55. Tennessee Valley Authority, National Fertilizer Development Center, Muscle Shoals, Ala.

Burks, J. E., III.
1978. Energy requirements for silviculture. N. Am. For. 1978:146–148.

Davis, C. H., and G. M. Blouin.
1977. Energy consumption in the U.S. chemical fertilizer system from the ground to the ground. Agric. Energy 1977:320–321.

Fertilizer Institute (The).
1979. The Fertilizer Institute energy use survey calendar year 1978. p. 2. The Fertilizer Institute, Washington, D.C.

McVickar, M. H., J. L. Snyder, Jr., and J. A. Burnett, Jr.
1966. Manufacturing processes for ammonia. *IN* Agricultural anhydrous ammonia technology and use. M. H. McVickar, W. P. Martin, I. E. Miles, and H. H. Tucker, eds. Agricultural Ammonia Institute, Memphis, Tenn.

Miller, R. E., and R. D. Fight
1979. Fertilizing Douglas-fir forests. 29 p. USDA For. Serv. Gen. Tech. Rep. PNW-83. USDA Forest Service, Portland, Oreg.

Smith, D. N., and E. W. Johnson.
1977. Silviculture: highly energy-efficient. J. For. 75(4):208–210.

Stickler, F. C., W. C. Burrows, and L. F. Nelson.
1975. Recognizing productive, energy-efficient agriculture in the complex U.S. food system. p. 1–3. Am. Soc. Agric. Eng. Annual Meet., Chicago, Ill. December 1975.

University of Washington, College of Forest Resources.
1979. Regional Forest Nutrition Research Project, Biennial Report 1977–78. Univ. Washington, Coll. For. Resour., Inst. For. Resour. Contrib. 37. 46 p. Univ. Washington, Seattle.

White, W. C.
1978. Energy food and fertilizers. Fert. Prog. 9(4):15, 18.