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FINAL REPORT

APPENDICES A, B, AND C

FEASIBILITY OF MEETING THE ENERGY NEEDS OF ARMY BASES WITH SELF-GENERATED FUELS DERIVED FROM SOLAR ENERGY PLANTATIONS

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This project thoroughly investigated the possibility of collecting and storing solar radiation in plants especially grown for their fuel value as a source of fuel on U. S. Army bases.

The study investigated the merit of producing this fuel at energy plantations at or near the bases. The fuel would be used for directly fired steam generators, hot water heaters, space heaters, and cooking.

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The research examined the major characteristics of energy plantations; analyzed plant-matter production rates from deciduous plants; and examined fuel consumption in stationary facilities at major troop training centers. The possibilities and requirements of energy plantations at Fort Benning, Fort Leonard Wood, and at Army bases in general were detailed.

It was concluded that energy plantations could be feasible at approximately 15 large Army bases and that the cost of solid fuel produced from them would be approximately $1/1 million Btu; the cost of synthetic natural gas produced from plants was determined to be approximately $3.10 to $4.20/1000 standard cu ft.

Besides being a perpetually renewable fuel source, it was found that energy plantations could provide independence from other fuel sources, reduction in future environmental problems caused by present fuels, and will productively use land not now in active use.

TABLE OF CONTENTS

APPENDIX A

ANALYSIS OF FUELS REQUIREMENTS FOR FIXED INSTALLATIONS AT MAJOR TROOP TRAINING CENTERS

TABLE OF CONTENTS

I. INTRODUCTION

The purpose of this appendix is to examine fuels consumption in fixed facilities at large troop training centers and proving grounds operated by the Army in the continental United States to determine whether:

- there are patterns of fuels consumption which can be used for broadly evaluating the merit of using Energy Plantations to supply fuels for fixed-facility purposes at Army bases; and whether
- consideration of fuels consumption in fixed facilities at Fort Benning and Fort Leonard Wood is a realistic basis for drawing conclusions about the merit of Energy Plantations for other bases in other localities.

It is concluded that with due allowance for the climate and enclosed floor area at individual troop training centers and proving grounds, there is an approximately predictable pattern of fuels use in fixed facilities for evaluating the merit of Energy Plantations at particular bases. It is also concluded that Fort Benning and Fort Leonard Wood are sufficiently representative of fuels consumption in fixed facilities at Army bases in general, again after allowance for climate and for floor area, that conclusions drawn with respect to them can be extended fairly reliably to other bases.

Fuels considered in this appendix are those used at Army bases in directly fired steam generators, hot-water heaters, and space heaters and for cooking. Fuels used for generating electricity in fixed generating facilities at bases are therefore included. Fuels used in mobile and transportation equipment are not considered, nor is consideration given to the fuels consumed for producing electricity purchased from sources outside Army bases.

Arsenals and Army installations in relatively densely populated localities are not considered in this analysis. Aberdeen Proving Ground, Edgewood Arsenal, Fort Belvoir and Fort Myer, for instance, are therefore excluded. Installations having land areas less than 32,000 acres are also excluded. Many installations have been excluded from consideration because they fall within the bounds of both of these restrictions.

Several outstanding characteristics of the fuels-consumption profiles at the larger troop training centers in unurbanized localities are identified in the course of the analysis discussed in this appendix. These characteristics will have considerable bearing on the design of Energy Plantations and associated fuels-processing systems proposed for meeting the fuels requirements for fixed facilities at large troop training installations. Among the more striking characteristics are the following:

- practically no coal or other solid fuels are used these days at Army bases in unurbanized localities -- natural gas and unknown amounts of LPG are widely used in southern and many midwestern localities, while fuel oils are the major fuel in the more northern sites;
- generally at least half and often as much as three-quarters or more of the fuels used (expressed as Btu) are consumed in unattended isolated heaters -- the vast majority of these heaters have firing capacities of less than 750,000 Btu per hour,and only a few have capacities as great as 3.5 million Btu per hour or greater;
- high-pressure boilers, taken as a class of direct-fired equipment, generally are the second-largest stationary consumer of fuels in army bases -- often accounting for as much as twenty-five percent but rarely more than fifty percent of the fuels used (expressed as Btu) at troop training centers and proving grounds; and

- the seasonal pattern of fuels consumption at Army bases appears to be approximately predictable -- it peaks in winter, as is to be expected, and fuels consumption in January may be as little as 2.5 times the average consumption rate in summer months in southern locations and as much as five or more times the summer rate at bases in the north.

Information on fuels consumption in fixed facilities at Army installations is quite limited. The analysis described in this appendix relies heavily on data compiled by the Corps of Engineers for Federal fiscal year 1971[1], on a report prepared by Harold D. Hollis in 1974[2], and on a study by Von Nida issued in 1974[4].

II. FUELS REQUIREMENTS FOR FIXED FACILITIES

Consumption of energy from fuels in Federal fiscal year 1971 for fixed facilities at twenty-two Army installations is summarized in Table A-I. These data are abstracted from a compilation prepared by the Corps of Engineers[1]. The installations included in the table:

- are located in lightly populated areas in North America,
- have a land area of at least 32,000 acres (50 square miles) each, and
- consumed the equivalent of at least 200 billion Btu in fuels as fired in fixed facilities in fiscal year 1971.

An estimated normal number of heating degree-days per year is shown for each installation, and the installations are arranged in the table in ascending order of degree-days per year. The degree-day data are estimated from information available from the National Climatic Center[3].

Other information for each of the Army installations for fiscal year 1971 shown in Table A-I is:

- consumption of energy from fuels in fixed facilities per thousand square feet of enclosed floor space -- the enclosed floor space areas (not shown in the table) compiled in reference 1 were used for computing this ratio; and
- consumption of energy from fuels per square foot of enclosed floor space per estimated normally expected heating degree-day per year.

No consistent pattern between the coolness of winter as reflected by normally expected heating degree-days per year on the one hand and Btu consumed per thousand square feet of enclosed building space in fiscal year 1971 on the other is discernible from Table A-I. At best, it can be said on the average that in localities in the lower forty-eight states where over 3,000 degree-days are normally expected every year, about thirty-five percent more fuel expressed in terms of its heating value as fired is consumed per unit of enclosed building area than in those localities where fewer than 3,000 degree-days per year can be expected. If all fixed installations on Army bases were equipped with the same thermal insulation, if the same fraction of fuel consumed at each base were used for heating water and cooking, and if buildings at each base were heated to the same temperature inside and used for the same purposes, a direct relationship between fuels requirements and heating degree-days per year would be expected. Such, at least on the basis of the information in Table A-I, does not appear to be the case.

However, when the fuels requirements are expressed in terms of Btu per square foot per degree-day, there appears to be somewhat more orderliness in the data. This ratio is in the nature of an overall heat-transfer coefficient. However, this analogy should not be pushed too far. The fuel consumptions used as a numerator in computing the ratio are the sums of fuels consumed for space and water heating, cooking and probably other purposes in fixed facilities; and the relative amounts of fuel used for these several purposes undoubtedly varies widely between the Army installations in Table A-I. While keeping this reservation in mind, it will be noted, nevertheless,that the ratio tends to decline sharply as the expected degree-days per year increases to about 2,600. Then as degree-days increase further, the ratio continues to decline but at a very much slower rate. This point is illustrated in Figure A-I. The dotted line ABC is

TABLE A-I

CONSUMPTION OF ENERGY FROM FUELS IN FIXED FACILITIES AT SELECTED ARMY INSTALLATIONS IN FISCAL YEAR 1971

Installation	Estimated Normal Degree-Days Per Year	Consumption of Energy From Fuels in FY 1971: Billion Btu	Million Btu Per 10^3 ft^2	Btu Per ft^2 Per Degree-Day
Fort Polk, La.	1,900	1,578	179	94
Fort Hood, Texas	2,000	1,623	102	51
Fort Stewart, Ga.	2,000	623	93	47
FORT BENNING, GA.	2,400	2,387	112	47
Fort Gordon, Ga.	2,500	1,524	170	68
Fort Jackson, S.C.	2,600	1,387	156	60
Fort Bliss, Texas	2,700	1,589	93	34
Fort McClellan, Ala.	2,900	518	108	37
Fort Bragg, N.C.	3,100	2,772	126	41
Fort Sill, Okla.	3,100	1,602	122	39
Fort Huachuca, Ariz.	3,700	493	77	21
Fort Campbell, Ky.	3,800	1,580	124	33
Fort Knox, Ky.	4,600	3,073	161	35
FORT LEONARD WOOD, MO.	4,800	2,165	170	35
Fort Dix, N.J.	5,000	2,382	198	40
Fort Riley, Kans.	5,100	1,993	164	32
Fort Lewis, Wash.	5,500	2,327	119	22
Fort Carson, Colo.	6,500	1,851	199	31
Camp Drum, N.Y.	7,400	314	190	26
Fort Greely, Alaska	9,000	212	141	16
Fort Richardson, Alaska	9,000	1,714	321	36
Fort Wainwright, Alaska	9,000	2,124	316	35

Sources:

Second column: based on information from reference 3.
Third column: reference 1.
Fourth column: reference 1 and third column.
Fifth column: second and fourth columns.

an approximate representation of the upper level of the range of the ratio when it is plotted against degree-days, and the line DEF is the approximate lower limit. The reason for the sharp change in slope which appears to occur at about 3,000 degree-days per year is not immediately clear. It certainly cannot be due solely, however, to a possible lack of thermal insulation in Army buildings in localities where fewer than 3,000 degree-days per year are to be expected. If such limited use of insulation in warmer winter climates were a major factor, the slope of the data would be expected to decline with decreasing degree-days per year in localities where insulation may not be widely used, rather than increasing as the data in Table A-I suggest.

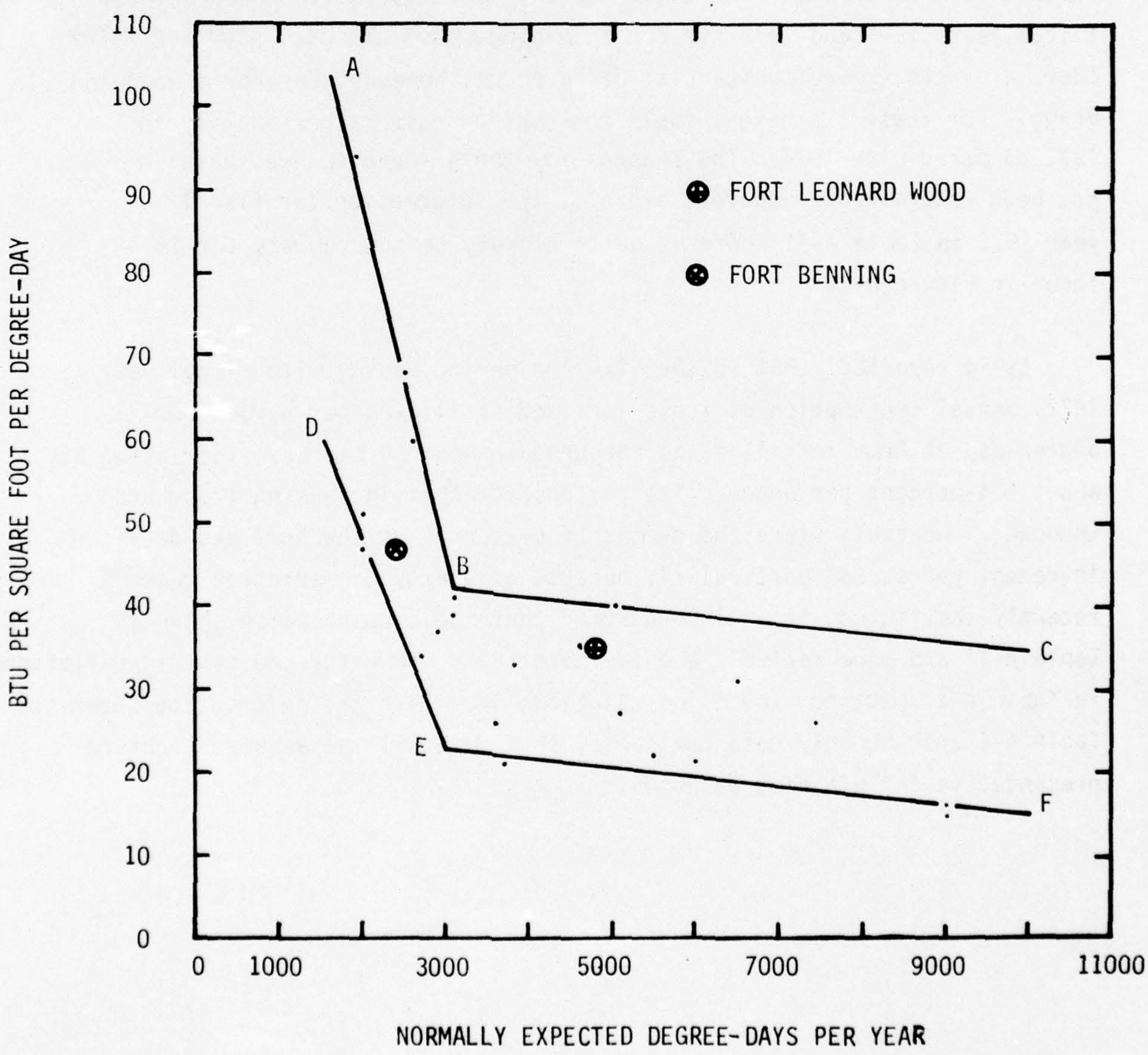
The wide scatter of the ratios plotted in Figure A-I is without doubt attributable to many causes, including, among others, the following:

- actual degree-days for fiscal year 1971 at particular Army installations were variously above or below the normally expected values;
- variation between installations in the relative amounts of fuels used for space heating, hot water, cooking and other fixed-facility requirements; and
- activity level at specific installations.

Despite the crudeness of the relationship represented in the figure, the estimates in Table A-I suggest that fuels consumption in fixed facilities at Fort Leonard Wood in fiscal year 1971 was approximately representative of consumption rates for Army installations in rural localities where 3,000 or more degree-days are normally expected every year. The corresponding consumption at Fort Benning was more representative of that at localities where fewer than 3,000 degree-days per year are normally expected.

FIGURE A-I

BTU PER SQUARE FOOT OF ENCLOSED BUILDING SPACE PER DEGREE-DAY IN FISCAL YEAR 1971 VERSUS ESTIMATED NORMAL DEGREE-DAYS PER YEAR FOR ARMY INSTALLATIONS SHOWN IN TABLE A-I



Because the fuels-consumption data summarized in Table A-I are for a single year, namely Federal fiscal year 1971, they may or may not be realistic for planning purposes. Fuels consumption can be expected to vary from year to year, as already noted, for instance because of variations in weather and activity at particular Army installations. This point is illustrated in Table A-II by data from Von Nida[4] for fiscal year 1973 for six of the installations shown in Table A-I. By comparing the values for Btu per square foot per degree-day installation by installation in the two tables, it will be seen that there are only moderate differences between fiscal years 1971 and 1973 for Forts Benning, Knox, Leonard Wood and Riley. There are rather more substantial differences, however, for Forts Hood and Bragg. For these two bases, fuels consumption rose rather sharply in 1973 compared with 1971. The reasons for these sharp changes have not been determined. However, overall, the information for fiscal year 1973 in Table A-II conforms quite closely to the summary for 1971 shown in Figure A-I.

It is reported[4] that in the six-year period ending with fiscal year 1972, annual consumption of fuels in fixed facilities per person per degree-day at Army installations throughout the Army had been increasing at about 3.4 percent per annum. The reasons for this increasing trend are unknown[2]. However, since the number of personnel in the Army has declined in recent years, and particularly because of energy conservation measures recently instituted, it will be assumed that fuels consumption shown in Table A-II are more reliable a guide than those shown for the same installations in Table A-I. But for those installations for which the information shown in Table A-I are the only data available, that data will be assumed to be representative for planning purposes.

TABLE A-II

CONSUMPTION OF ENERGY FROM FUELS IN FIXED FACILITIES

AT SELECTED ARMY INSTALLATIONS IN FISCAL YEAR 1973

Installation	Estimated Normal Degree-Days Per Year	Consumption of Energy From Fuels in FY 1973		
		Billion Btu	Million Btu Per 10^3 ft^2	Btu Per Ft^2 Per Degree-Day
Fort Hood, Texas	2,000	2,087	131	66 (51)*
FORT BENNING, GA.	2,400	2,512	116	48 (47)*
Fort Bragg, N.C.	3,100	4,161	196	63 (41)*
Fort Knox, Ky.	4,600	3,560	180	39 (35)*
FORT LEONARD WOOD, MO.	4,800	2,082	166	35 (35)*
Fort Riley, Kans.	5,100	2,048	169	33 (32)*

Sources:

Second column: based on information from reference 3.

Third column: reference 4.

Fourth colunn: reference 4 and third column.

Fifth column: second and fourth columns.

*Data for fiscal year 1971 in parentheses (see Table A-I).

III. FUEL CAPACITIES OF FIRED EQUIPMENT AT FIXED FACILITIES

Directly fired space and water-heating equipment at army installations are classified into four firing-rate ranges by the Army. These equipment classes are defined as follows[2]:

- high-pressure boilers having firing rates of 3.5 million Btu per hour or greater, used for generating saturated steam at 135 psia or higher or, in a few instances, superheated steam at higher pressures, and for generating high-temperature water--high-pressure boilers are usually located in boiler plants with operators in attendance and may be modern units equipped for firing oil or gas but often are older, formerly coal-fired units which have been refitted for oil or gas;
- large heating plants having firing rates of 3.5 million Btu per hour or greater, used for producing hot water at lower temperatures than in high-pressure boilers or, in some instances, for generating steam at lower pressures than in high-pressure boilers--these units may be isolated or in central plants, and they may be attended or unattended--they may be modern units designed for oil or gas firing, or may be older units originally designed for coal but later refitted for oil or gas;
- intermediate heating plants having firing rates between about 750,000 and 3.5 million Btu per hour used for water heating, low-pressure steam, and space heaters--these units are usually isolated, often unattended and generally fired with gas or oil; and
- small heating plants having firing rates below about 750,000 Btu per hour used for hot water or space heating--nearly all these units are isolated, unattended and fired with oil or gas.

Cooking stoves represent another substantial source of fuel demand. Some of these units may be oil fired, but most of them use gas.

The relative amounts of fuel consumed in high-pressure boilers and heating plants vary widely among Army installations. This point is illustrated in Table A-III where fuel consumptions in high-pressure boilers and in each of the three classes of heating plants are expressed as percentages of total fuel energy used in fiscal year 1971 at the Army installations shown in Table A-I. The installations are arranged in the order of increasing normally expected heating degree-days per annum at their respective localities. The installations, therefore, are arranged in the same order as in Table A-I. The information shown in Table A-III is believed to include fuel used in cooking stoves.

The information for the Army installations shown in Table A-III indicates that for fiscal year 1971:

- small heaters used very large fractions of the fuels consumed in fixed facilities at all the Army installations other than the three in Alaska, and were in fact the largest single class of consumers in fifteen of the nineteen installations located in the forty-eight contiguous states;
- while intermediate-sized heaters in most instances (eighteen out of the nineteen installations in the lower forty-eight states) accounted for twenty percent or less of the total fuels consumed in fixed facilities, the sum of the fuels consumed in small and intermediate-sized heaters accounted for more than fifty percent (and frequently very much more) in eighteen of the nineteen installations in the lower forty-eight states;
- in seven instances, high-pressure boilers were the largest single class of consumers, although only four of these instances were among the nineteen installations in the lower forty-eight states, and

except for the Alaskan installations, fuels use in high-pressure boilers was not greater than half the total fuels used in any of the nineteen installations in the contiguous states; and

- large heaters consumed only a relatively small fraction of the total fuels consumed at any of the installations--in fact, less than nine percent in seventeen of the twenty-two installations shown in the table.

No relationships are discernible between the fraction of the fuels consumed in high-pressure boilers or in any class of heater on the one hand, and either total fuels consumption at individual installations or the normally expected heating degree-days per year at the installations on the other hand.

The limited data available[2] for fiscal year 1973 for installations included in Table A-III indicate approximately the same fuels-consumption distribution between high-pressure boilers and heaters as in 1971 (see Table A-IV). Thus, the fraction of total fuels consumed in fiscal year 1973 at each of the six installations shown in the table by:

- large heaters is small;
- high-pressure boilers is half or considerably less than half of the total fuels consumed, although it is in every instance a larger fraction than in 1971; and
- intermediate and small heaters taken together consumed the largest fraction in 1973 in all instances except at Fort Hood, although except at Fort Benning and possibly at Fort Riley the fraction consumed by these two classes of heaters was smaller in 1973 than in 1971.

TABLE A-III

CONSUMPTION OF ENERGY FROM FUELS IN FISCAL YEAR 1971 AT

SELECTED ARMY INSTALLATIONS BY CLASS AND CAPACITY OF DIRECTLY FIRED EQUIPMENT

Installation	Estimated Normal Degree-Days Per Year	Total Fuels Consumption Billion Btu	Percent of Total Fuels Consumption			
			High-Pressure Boilers	Large Heaters	Intermediate Heaters	Small Heaters
Fort Polk, La.	1,900	1,578	8	<1	<1	91
Fort Hood, Texas	2,000	1,623	7	8	8	76
Fort Stewart, Ga.	2,000	623	35	3	18	44
FORT BENNING, GA.	2,400	2,387	41	1	2	56
Fort Gordon, Ga.	2,500	1,524	49	-	9	42
Fort Jackson, S.C.	2,600	1,387	49	1	4	46
Fort Bliss, Texas	2,700	1,589	8	11	10	71
Fort McClellan, Ala.	2,900	518	34	4	11	51
Fort Bragg, N.C.	3,100	2,772	42	<1	13	44
Fort Sill, Okla.	3,100	1,602	11	13	20	56
Fort Huachuca, Ariz.	3,700	493	29	11	8	52
Fort Campbell, Ky.	3,800	1,580	46	1	1	52
Fort Knox, Ky.	4,600	3,073	20	4	18	58
FORT LEONARD WOOD, MO.	4,800	2,165	26	1	10	63
Fort Dix, N.J.	5,000	2,382	50	7	7	36
Fort Riley, Kans.	5,100	1,993	13	11	11	65

TABLE A-III

(continued)

CONSUMPTION OF ENERGY FROM FUELS IN FISCAL YEAR 1971 AT

SELECTED ARMY INSTALLATIONS BY CLASS AND CAPACITY OF DIRECTLY FIRED EQUIPMENT

Installation	Estimated Normal Degree-Days Per Year	Total Fuels Consumption Billion Btu	Percent of Total Fuels Consumption			
			High-Pressure Boilers	Large Heaters	Intermediate Heaters	Small Heaters
Fort Lewis, Wash.	5,500	2,327	45	2	12	41
Fort Carson, Colo.	6,500	1,851	22	2	14	62
Camp Drum, N.Y.	7,400	314	6	19	29	46
Fort Greely, Alaska	9,000	212	80	4	4	12
Fort Richardson, Alaska	9,000	1,714	88	5	2	6
Fort Wainwright, Alaska	9,000	2,124	95	3	1	2

Source: Reference 1.

The preeminence of small and intermediate-capacity heaters as consumers of fuels at the larger Army installations in unurbanized localities is reflected by their number relative to the number of large-capacity heaters and high-pressure boilers in use. A "census" of the various classes and capacities of directly fired equipment at a representative list of troop training centers is shown in Table A-V. The overwhelming numbers of small and intermediate-capacity heaters is a significant factor bearing on the selection of the most appropriate type of fuel to be recommended for production from Energy Plantations proposed for serving Army installations (see Appendix B).

It is evident from this analysis that if Energy Plantations are to be a major source of fuel for fixed facilities at large troop training centers, a substantial part of the fuel derived from the plantations must be suitable for firing in unattended equipment, much of which has a fuel capacity of less than 750 thousand Btu per hour. This type of equipment evidently generally accounts these days for more than half, and frequently for three-quarters or more, of the total fuel consumed in fixed facilities at troop training centers in the forty-eight contiguous states.

High-pressure boilers are often the second-largest total consumer of fuels in fixed facilities at Army training bases in unurbanized localities. However, their consumption is usually a considerably smaller part of the total fuel consumed in fixed facilities than is the total consumption in small and intermediate heaters. Therefore, if fuel derived from Energy Plantations is tailored specifically to meet the requirements of high-pressure boilers, and if this tailoring makes the fuel unsuitable for small and intermediate-capacity heaters, Energy Plantations cannot be a major fuels source for large troop training centers as they are now equipped for meeting space and water-heating requirements. On the other hand, if the fuel derived from Energy Plantations is suitable for use in small and intermediate-capacity heaters and also in high-pressure boilers, Energy Plantations could provide essentially all the fuel used in the fixed facilities at training bases in the forty-eight contiguous states.

TABLE A-IV

CONSUMPTION OF ENERGY FROM FUELS IN FISCAL YEAR 1973 AT SELECTED ARMY INSTALLATIONS BY CLASS AND CAPACITY OF DIRECTLY FIRED EQUIPMENT

Installation	Estimated Normal Degree-Days Per Year	Total Fuels Consumption Billion Btu	Percentage of Total Fuels Consumption: High-Pressure Boilers	Percentage of Total Fuels Consumption: Large Heaters	Percentage of Total Fuels Consumption: Intermediate and Small Heaters
Fort Hood, Texas	2,000	2,087	50 (42)*	4	46 (57)*
FORT BENNING, GA.	2,400	2,512	8 (7)*	8	84 (84)*
Fort Bragg, N.C.	3,100	4,161	49 (41)*	1	50 (58)*
Fort Knox, Ky.	4,600	3,560	26 (20)*	6	67 (76)*
FORT LEONARD WOOD, MO.	4,800	2,082	31 (26)*	2	67 (73)*
Fort Riley, Kans.	5,100	2,048	15 (13)*	12	73 (74)*

Source: Reference 2.

*Data for fiscal year 1971 in parentheses (see Table A-III)

TABLE A-V

NUMBERS AND FIRING CAPACITY OF DIRECT-FIRED EQUIPMENT AT A REPRESENTATIVE LIST OF TROOP TRAINING CENTERS

Installation	Total Direct-Fired Units	Numbers of High-Pressure Boilers	Numbers of Heaters by Firing Capacity Million Btu per Hour		
			>3.5	3.5-0.75	<0.75
Fort Bragg, N. C.	6,213	9	13	99	6,092
Fort Campbell, Ky.	2,776	31	2	88	2,655
Fort Knox, Ky.	1,503	22	34	145	1,302
FORT LEONARD WOOD, MO.	1,545	6	9	56	1,474
Fort Riley, Kans.	1,055	4	65	346	640
Fort Carson, Colo.	2,538	4	39	82	2,413

Source: Reference 2.

IV. TYPES OF FUEL USED IN FIXED FACILITIES

Coal is not used these days in substantial quantities at troop training centers in the contiguous forty-eight states[2]. Gas is the major source of heat at installations in the South and in many localities in the Midwest, and oil is more likely to be so at posts in the North[2]. This point is illustrated by data compiled for a recent period by the Defense Energy Information System (see Table A-VI). The total fuel consumptions shown in the table for the indicated bases are moderately different from the consumptions reported for the same bases in Table A-I for Federal fiscal year 1971, and are lower than reported in Table A-II for fiscal year 1973. As previously noted, fuels consumption at large troop training centers was generally slightly to substantially higher in fiscal 1973 than in 1971. These differences between information sources in reported fuel consumption do not cloud the overall conclusion to be drawn from the data in Table A-VI and qualitatively confirmed in reference 2, to wit:

- natural gas and unknown quantities of LPG are the major sources of heat for fixed facilities at large troop training centers in most localities except in the North and Northeast, and
- solid fuels, coal in particular, are not a major source of energy for fixed facilities in any of the larger troop training installations operated by the Army.

Fuels consumption for fixed facilities at Fort Benning in Federal fiscal year 1973 conformed completely to these general conclusions (see Table A-VII). At Fort Leonard Wood, however, oil accounted for about sixty-nine percent of the heat produced in 1973, gas accounting for substantially all the remainder (see Table A-VIII). Coal is not an important factor at Fort Leonard Wood or Fort Benning.

Table A-VI

FUELS CONSUMPTION BY FUEL TYPE
AS A FUNCTION OF LOCATION FOR REPRESENTATIVE ARMY INSTALLATIONS

Installation and Location	Estimated Normal Degree-Days Per Year	Fuel Consumption - Billion Btu				Distribution of Fuel Consumption-Percent of Total Consumption		
		Total	Gas	Oil	Coal	Gas	Oil	Coal
Fort Hood, Texas	2,000	1,700	1,698	1	--	99+	1	--
FORT BENNING, GA.	2,400	2,073	1,893	179	--	91	9	--
Fort Bragg, N. C.	3,100	3,013	2,032	957	25	67	32	1
Fort Knox, Ky.	4,600	2,950	2,482	390	79	84	13	3
Fort Lewis, Wash.	5,500	2,494	124	2,370	--	5	95	--

Source: Defense Energy Information Service as per reference 2.

TABLE A-VII

FUELS CONSUMPTION IN FEDERAL FISCAL YEAR 1973
FOR FIXED FACILITIES AT FORT BENNING

Direct-Fired Equipment Type	Fuels Consumption - Billion Btu: Gas	Oil	Coal
High-Pressure Boilers:	1,235	--	--
Large Heaters:	34	--	--
Intermediate Heaters:	36	5	--
Small Heaters:	993	199	12
Totals:	2,298	204	12
Grand Total:		2,514	
Percent of Grand Total:	91	8	<1

Sources: References 4 and 5.

TABLE V-III

FUELS CONSUMPTION IN FEDERAL FISCAL YEAR 1973 FOR FIXED FACILITIES AT FORT LEONARD WOOD

	Fuels Consumption - Billion Btu		
Direct-Fired Equipment Type	Gas	Oil	Coal
High-Pressure Boilers:	77	557	14
Large Heaters:	9	22	--
Intermediate Heaters:	26	153	--
Small Heaters:	525	696	--
Totals:	637	1,428	14
Grand Total:		2,079	
Percent of Grand Total:	31	69	<1

Sources: References 4 and 5.

V. SEASONAL FUEL CONSUMPTION AT FIXED FACILITIES

The seasonal variation in heating load is an influential factor in the performance requirements of Energy Plantations and their associated fuels-processing systems designed for supplying fuel for fixed facilities at troop training centers. Few data have been compiled, however, on the changes in heating load through the year at major troop bases in unurbanized localities. There are no seasonal data, for instance, for Fort Benning or Fort Leonard Wood, but partial data are available for Forts Bragg, Meade and Belvoir[4]. No seasonal data are known to exist for any other large troop center[5,6].

The partial data available for the three bases named in the preceding paragraph are for groups of high-pressure boilers which are generally operated all year. The data for Fort Bragg are for four such boilers which consumed about twenty-four percent of all the fuels (expressed as Btu as fired) used at the base in Federal fiscal year 1973.

The shapes of the heating-load profiles through the year reported for high-pressure boilers at Forts Bragg, Meade and Belvoir are quite similar. During the warmer months, there is a base load which is about a third of the general load level in the colder months. The base load in the warm season is represented primarily by mess hall and hot-water needs. The difference between the loads in the warm and cold seasons is the space-heating requirement in wintertime. The loads in each of these major seasons are remarkably uniform, and the seasons are separated by approximately one-month periods during which the load level is intermediate between the two major seasonal loads. The heat-load seasonal profile for the four high-pressure boilers at Fort Bragg for which seasonal data are available as a group is shown by the dotted line in Figure A-II. These heat-load data were provided by Von Nida[4]. Comparable graphical presentations for Forts Meade and Belvoir are included in reference 2.

Because of the similarity between the seasonal heat-load profiles at Forts Bragg, Meade and Belvoir, and because Fort Bragg meets the criteria described on page A-5 of this Appendix, it was decided to use the Bragg data as the basis for estimating seasonal heating loads at other large training centers in unurbanized localities[5]. Centers in the more heavily urbanized localities, such as is the case for Forts Meade and Belvoir, frequently do not have land areas adequately large on site or nearby for Energy Plantations with a potential fuels-production capacity comparable with the fuels demand of the fixed facilities at the centers.

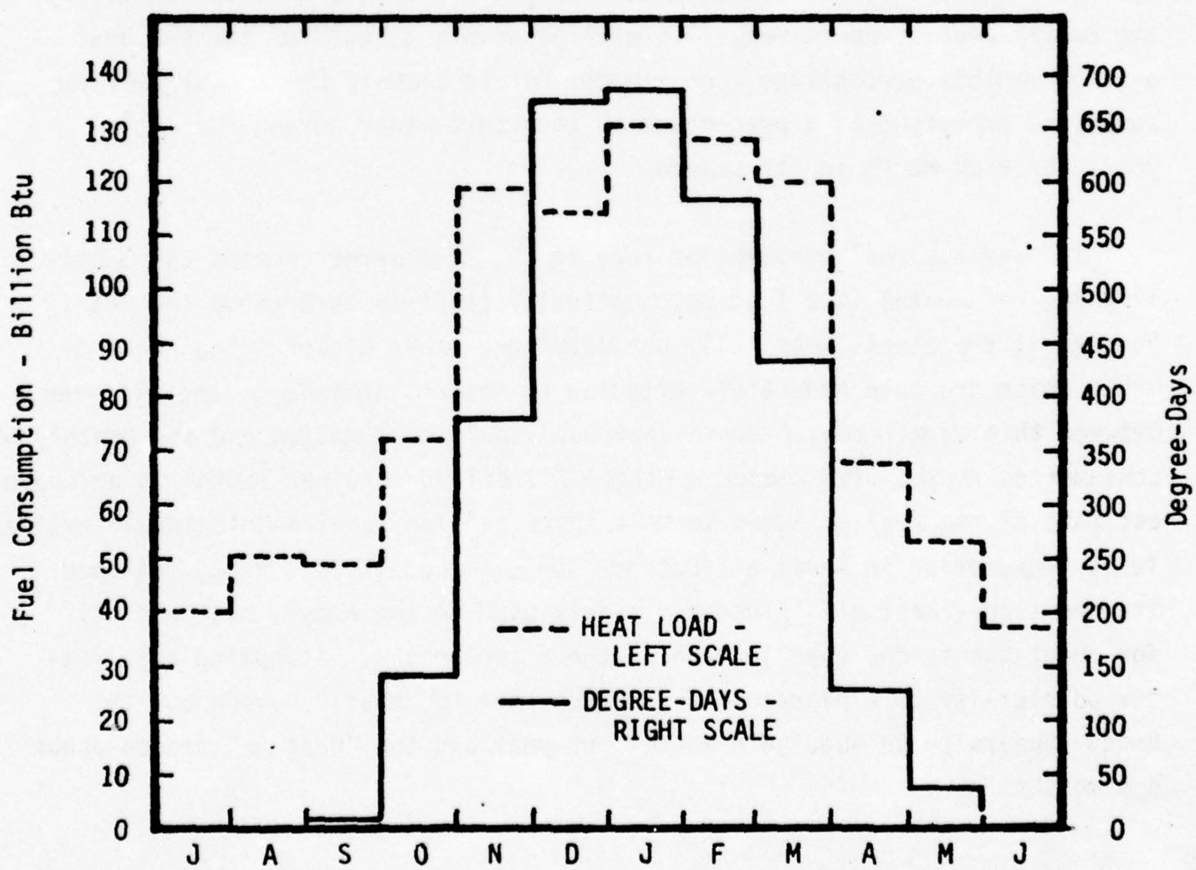
The heat loads by months for Federal fiscal year 1973 for the previously mentioned group of four high-pressure boilers at Fort Bragg are compared in Figure A-II with the estimated normally expected heating degree-days, also by months, in the vicinity of the base. The degree-day data are for Fayetteville, North Carolina, the meteorological station nearest to Fort Bragg. It will be seen that in the five months when the normally expected degree-days are fewer than fifty, the heat load ranges from slightly less than 40 to slightly over 50 billion Btu per month. The average heat load during this warm season was about 46 billion Btu per month.

In the five-month period during which estimated normally expected degree-days exceed three hundred per month, the heat load varied from about 110 to about 130 billion Btu per month. The load averaged about 123 billion Btu during this period. In October and April, when estimated normally expected degree-days are about 135 per month, the heat load was about 70 billion Btu per month.

FIGURE A-II

FUEL CONSUMPTION PROFILE FOR FOUR HIGH PRESSURE BOILERS AND ESTIMATED NORMAL DEGREE-DAYS COMPARED

FORT BRAGG - FEDERAL FISCAL 1973



Sources: Heating degree-days - reference 3
Heat load data - reference 4

The fuel consumption shown in Figure A-II in each month by the four high-pressure boilers is expressed in Table A-IX as a percentage of their total consumption during the entire year. The monthly percentage for each of the five warmer months (May through September) is compared with the average of the monthly percentages (4.7 percent) during the five-month period. Similarly, comparison is made for the five colder months (November through March) and for the two intermediate months (April and October) for which the monthly averages for each season are 12.5 and 7.0 percent of the consumption during the entire year, respectively. It will be seen that each of the seasonal average monthly percentages approximates fairly closely the actual fuel consumption, expressed as a percentage of the consumption during the entire year, for each month in its season.

The average fuel consumption rate in the five warmer months (46.3 billion Btu per month) is a load which actually persists throughout the year, because it represents mess hall, hot water and other housekeeping requirements which are only moderately affected by season. Therefore, the difference between this warmer-season-monthly-average fuels consumption and the monthly average consumption in the five cooler months(122.7 billion Btu per month) is an approximate estimate of the fuel consumed to meet space-heating requirements in wintertime. The fuels consumption in April and October suggest that if Fort Bragg followed the "heat on - heat off" procedure widely used in the Army[2], heat was off for about twenty-one days in each of these two months. Accepting this latter possibility as a plausible assumption, the "heat off" season at Fort Bragg appears to be about 6.5 months per year and the "heat on" season about 5.5 months.

At troop training centers where most of the personnel are housed on base, where manufacturing or other operations not directly associated with troop training are about "average" for bases primarily devoted to troop training,

TABLE A-IX

FUEL-CONSUMPTION PROFILE BY MONTHS IN
FOUR HIGH-PRESSURE BOILERS AT FORT BRAGG

	Fuel Consumption			
Month	Billion Btu	Percent of Total for Year	Seasonal Monthly Average Percent of Total for Year	Ratio of Monthly to Seasonal Average Percentages
July	40.6	4.1	4.7	0.87
August	50.8	5.2	4.7	1.11
September	49.1	5.0	4.7	1.06
October	71.9	7.3	7.0	1.04
November	118.4	12.0	12.5	0.96
December	114.3	11.6	12.5	0.93
January	130.8	13.3	12.5	1.06
February	128.9	13.1	12.5	1.05
March	120.9	12.3	12.5	0.98
April	67.1	6.8	7.0	0.97
May	53.3	5.4	4.7	1.15
June	37.8	3.9	4.7	0.83
Totals	983.9	100.0	100.0	----

Source: Reference 4.

and where consumption of electricity generated outside the base is also about "average" for troop training centers, it would be expected that fuels consumption in fixed facilities:

- for purposes other than space heating will vary more or less directly with the scale of operations at the center, and
- for space-heating purposes will vary with the scale of operations and with the severity of winter at the center.

If these premises be accepted, and if it is also assumed that:

- the seasonal pattern of fuels consumption in the four high-pressure boilers for which seasonal fuels-use data are available for Fort Bragg is essentially the same as the seasonal pattern for total fuels consumption in fixed facilities at Fort Bragg, and that
- operations at Fort Bragg are similar in all respects, except possibly for scale, to operations generally in troop training centers,

then the fractional distribution of fuels consumption in fixed facilities at training centers for base-load purposes (mess halls, water heating and other housekeeping purposes which are not notably affected by season) and for space heating can be represented by the following relationship:

$$\frac{46.3 \times 10^9 \times 12}{983.9 \times 10^9} + \frac{(983.9 \times 10^9 - 46.3 \times 10^9 \times 12)}{983.9 \times 10^9} \times \frac{\text{Heating Degree-Days}}{3,100} = \text{An Index Number} \quad \text{(A-1)}$$

where the heating degree-days and index number are specific for a particular troop training center. The numerical values in the equation have the following significance:

- 46.3×10^9 Btu is the average monthly fuels consumption in the four high-pressure boilers at Fort Bragg during the warmer months (see Table A- IX) -- it is assumed to be equal to the base fuels demand per month for water heating, mess halls and other sources of fuels demand which do not vary with season through the year;
- 983.9×10^9 Btu is the total fuels consumption by the four high-pressure boilers at Fort Bragg in the year for which seasonal fuels consumption data are available at Fort Bragg, and
- 3,100 is the estimated normal number, rounded to the nearest hundred, of heating degree-days per year expected at Fort Bragg.

Equation A-1 reduces to the following:

$$0.565 + 1.403 \times 10^{-4} \text{ (Heating Degree-Days)} = \text{Index.} \qquad \text{(A-2)}$$

Given the total fuels consumption in a year and an estimate of the normally expected heating degree-days at a particular troop training center, equation A-2 can be used to make estimates of the fraction of the total fuels consumption during the year which is used for space heating and for base load. The estimate of the fuel used for space heating is:

$$\frac{\text{(Total Fuel For Year - Btu)} \times 1.403 \times 10^{-4} \text{ (Heating Degree-Days)}}{\text{Index}} \qquad \text{(A-3)}$$

and for base load is

$$\frac{\text{(Total Fuel For Year - Btu)} \times 0.565}{\text{Index}} \qquad \text{(A-4)}$$

As a check on the validity of equation A-2 and its general applicability to troop training centers, relationship A-3 has been used to estimate the overall space-heating requirement per square foot of enclosed floor area per normally expected heating degree-day per year for each of the Army installations listed in Tables A-I and A-II. For convenience, this ratio will be referred to as the space-heating loss coefficient. Its units are Btu per square foot of floor area per degree-day per year. Because of the general similarity of building construction at Army bases, it would be expected that the estimates of the space-heating loss coefficient for the installations shown in Tables A-I and A-II would tend to be about the same. Estimates of these coefficients are shown in the right-hand columns of Tables A-X and A-XI, respectively.

Referring specifically to Table A-X, it will be seen that half the estimated coefficients lie between fifteen and twenty. The average of all the coefficients is 17.9 Btu per square foot of floor area per degree-day per year.

The values for the estimated coefficients based on Federal fiscal 1973 data shown in Table A-XI are seen to be generally similar to those shown for the same bases in Table A-X. However, the values for Forts Hood and Bragg are twenty-nine and fifty-five percent higher, respectively, than the corresponding values shown for these bases for 1971 in Table A-X. The reason for the marked differences between 1971 and 1973 in the coefficient estimates for these two bases is unknown. The very high estimated value (27.5) for the coefficient at Fort Bragg in 1973 suggests that the reported total fuels consumption for Bragg in that year may be in error. However, even if it is, any error will not affect the validity of the coefficient estimates shown in Tables A-X and A-XI, because the total fuels consumption in fixed facilities at Fort Bragg is not a factor in developing equation A-2---only the fuel consumed in the four high-pressure boilers is.

TABLE A-X

ESTIMATED SPACE-HEATING LOSS COEFFICIENTS AT SELECTED ARMY INSTALLATIONS BASED ON FISCAL YEAR 1971 FUELS CONSUMPTION

Installation	Estimated Normal Degree-Days Per Year	Fuels Consumption Billion Btu		Space-Heating Loss Coefficient Btu/ft^2-Degree-Day/Year
		Total	Space Heating	
Fort Polk, La.	1,900	1,578	507	30.3
Fort Hood, Texas	2,000	1,623	539	16.9
Fort Stewart, Ga.	2,000	623	207	15.4
FORT BENNING, GA.	2,400	2,387	893	17.5
Fort Gordon, Ga.	2,500	1,524	584	25.1
Fort Jackson, S.C.	2,600	1,387	544	23.5
Fort Bliss, Texas	2,700	1,589	637	13.8
Fort McClellan, Ala.	2,900	518	217	15.6
Fort Bragg, N.C.	3,100	2,772	1,206	17.7
Fort Sill, Okla.	3,100	1,602	697	17.1
Fort Huachuca, Ariz.	3,700	493	236	10.0
Fort Campbell, Ky.	3,800	1,580	766	15.8
Fort Knox, Ky.	4,600	3,073	1,638	18.7
FORT LEONARD WOOD, MO.	4,800	2,165	1,178	19.3
Fort Dix, N.J.	5,000	2,382	1,320	21.9
Fort Riley, Kans.	5,100	1,993	1,114	18.0
Fort Lewis, Wash.	5,500	2,327	1,343	12.5
Fort Carson, Colo.	6,500	1,851	1,142	18.9
Camp Drum, N.Y.	7,400	314	203	16.6
Fort Greely, Alaska	9,000	212	146	10.8
Fort Richardson, Alaska	9,000	1,714	1,184	24.6
Fort Wainwright, Alaska	9,000	2,124	1,468	24.3

Sources:
- Second column: based on information from reference 3.
- Third column: reference 1.
- Fourth column: reference 1 and equations A-2 and A-3.
- Fifth column: second and fourth columns and floor area information from reference 1.

It is concluded on the basis of the relative uniformity of these estimates of space-heating loss coefficients that the relationship represented by equation A-2 is approximately valid. It is being accepted, therefore, as the basis for estimating space-heating loads at Army training centers and, therefore, also as one of the elements for estimating the profile through the year of fuels consumption for fixed facilities at training centers in unurbanized localities.

Incidentally, this analysis of fuels-consumption profiles sheds light on the reason for the shape of the trend of the data shown in Figure A-I. The base fuels demand represented by consumption in mess halls, hot-water heaters and for other purposes which are little affected by season is evidently a very substantial part of the total demand for fuels in fixed facilities at troop training centers. As degree-days increase in localities where winters are relatively mild, total fuels demand, including both the base demand and the space-heating load, increases only slowly because space-heating load is only a relatively small part of the total demand. Where winters are more severe, total fuels demand increases more rapidly with degree-days because space-heating load is a relatively large part of the total demand. As a consequence, fuels consumption per degree-day declines initially rapidly with increasing heating degree-days per year, and then the rate of decline becomes very much smaller as winters become more severe.

This point is illustrated in Table A-XII where equation A-2 has been used for estimating the relationship between Btu per square foot of enclosed building floor space per degree-day and normally expected degree-days per year, the coordinates used in Figure A-I. It will be seen that the scaled values in the sixth column of the table approximate the trend of the data shown in Figure A-I -- further evidence which suggests that equation A-2 is an approximately valid means for estimating the relationship between the fuel required for the base load and for space heating at a troop training center.

The profile through the year of fuels consumption in the fixed facilities at an Army training center also depends on the profile of heating degree-days through the year. These profiles for Forts Bragg, Benning and Leonard Wood are

TABLE A-XI

ESTIMATED SPACE-HEATING LOSS COEFFICIENTS AT SELECTED ARMY INSTALLATIONS BASED ON FISCAL YEAR 1973 FUELS CONSUMPTION

Installation	Estimated Normal Degree-Days Per Year	Fuels Consumption Billion Btu		Space-Heating Loss Coefficient Btu/ft^2-Degree-Day/Year
		Total	Space Heating	
Fort Hood,Texas	2,000	2,087	693	21.8
FORT BENNING, GA.	2,400	2,512	939	18.1
Fort Bragg, N.C.	3,100	4,161	1,810	27.5
Fort Knox, Ky.	4,600	3,560	1,897	20.9
FORT LEONARD WOOD, MO.	4,800	2,082	1,133	18.8
Fort Riley, Kans.	5,100	2,048	1,145	18.5

Sources:

Second Column: Based on information from reference 3.
Third column: reference 4.
Fourth column: reference 4 and equations A-2 and A-3.
Fifth column: second and fourth columns, and floor area information from reference 4.

summarized in Table A-XIII. The degree-day data are the normally expected values for Fayetteville, North Carolina; Columbus, Georgia;and Rolla, Missouri -- the meteorological stations nearest to each of the bases. These monthly data, expressed as percentages of the annual total expected heating degree-days are shown in Figure A-III. It will be seen that the relative profiles for each of the three bases are quite similar. It is concluded that the "heating seasons" at Forts Benning and Leonard Wood are probably,therefore,also about as long as at Fort Bragg, namely between five and six months per year starting in October and ending in April. On this basis and the reported total fuels consumption in Federal fiscal year 1973 (see tables A-VII and A-VIII), and assuming the validity of equation A-2, average fuels consumption profiles have been estimated for the fixed facilities at Forts Benning and Leonard Wood. These estimated average profiles are summarized in Table A-XIV.

It might be argued that for planning purposes,ranges or upper limits for the profiles are to be preferred over the normally expected estimated profiles shown in Table A-XIV. This question is addressed in Appendix D, sections III and IV.

As is to be expected, the estimated normal seasonal patterns of fuels consumption at Forts Benning and Leonard Wood peak in January. The peak demand for space heating throughout the country generally occurs in that month, but for Army installations the magnitude of the peak in relation to the year-long base fuels demand for mess halls, water heating and other housekeeping requirements which are not seasonally affected depends on the severity of winter at each particular Army installation. This point is illustrated in Table A-XV, where in the eighth column,estimates are shown of the ratio between the fuels requirements in summer months (the fifth column in the table) and normally expected total fuels demand for fixed facilities in the coldest month of the year (the seventh column). It will be seen that this ratio varies from about two to

TABLE A-XII

ESTIMATED EFFECT OF COLDNESS OF WINTER ON THE ANNUAL FUEL REQUIREMENT PER HEATING DEGREE-DAY PER YEAR PER SQUARE FOOT OF FLOOR AREA FOR FIXED FACILITIES AT TROOP TRAINING CENTERS

(Estimates are calculated using equation A-2)

Heating Degree-Days Per Year	Index Factor		Index	Index Per Degree-Day	
	Base Load	Space Heating		As Calculated x 10^3	Scaled to Match Data In Fig A-I
1,000	0.565	0.140	0.705	0.705	89
2,000	0.565	0.281	0.846	0.423	53
3,000	0.565	0.421	0.986	0.329	41
4,000	0.565	0.561	1.126	0.282	36
5,000	0.565	0.702	1.267	0.253	32
6,000	0.565	0.842	1.407	0.235	30
7,000	0.565	0.982	1.547	0.221	28
8,000	0.565	1.123	1.688	0.211	27
9,000	0.565	1.263	1.828	0.203	26

Sources:

First column: arbitrarily selected values.

Second and Third columns: calculated using equation A-2.

Fourth column: sum of values in second and third columns.

Fifth column: fourth column divided by first column and multiplied by 1,000.

Sixth column: values from fifth column multiplied by 125.8, the ratio of the average of the ordinates of the data points in Figure A-I divided by the average of the values in the fifth column.

nearly six for the range of winter severities (heating degree-days per year) shown in the table. The magnitude of the ratio is an important factor to be considered in the design of Energy Plantations and their associated fuels-processing facilities.

TABLE A-XIII

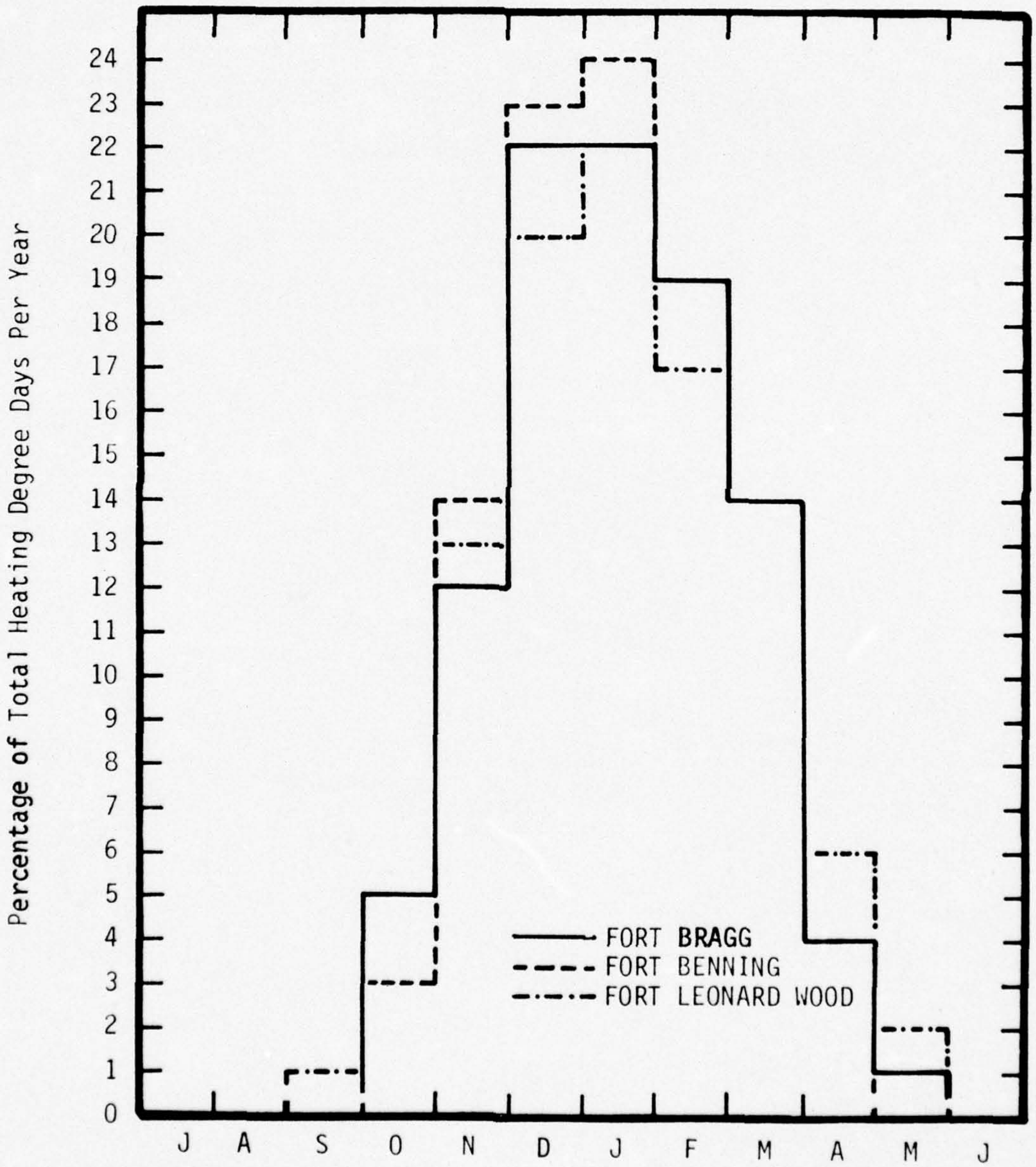
NORMALLY EXPECTED HEATING DEGREE-DAYS,
BY MONTHS, AT FORTS BRAGG, BENNING AND LEONARD WOOD

Month	Fort Bragg (Fayetteville, N.C.)	Fort Benning (Columbus, Ga.)	Fort Leonard Wood (Rolla, Mo.)
July	0	0	0
August	0	0	8
September	9	0	49
October	140	81	236
November	378	324	603
December	676	536	942
January	682	571	1,042
February	585	448	834
March	435	323	694
April	131	89	275
May	37	6	107
June	0	0	14
Annual Totals (Rounded)	3,000	2,400	4,800

Source: Reference 3.

FIGURE A-III

RELATIVE HEATING DEGREE-DAY PROFILES
AT FORTS BRAGG, BENNING AND LEONARD WOOD



Source: TABLE A-XIII

TABLE A-XIV

ESTIMATED AVERAGE FUELS CONSUMPTION PROFILES
FOR FIXED FACILITIES AT FORTS BENNING AND LEONARD WOOD

Billions of Btu

Month	Fort Benning			Fort Leonard Wood		
	Base Load	Space Heating	Total	Base Load	Space Heating	Total
July	131	-	131	79	-	79
August	131	-	131	79	-	79
September	131	-	131	79	-	79
October	132	42	174	79	51	130
November	131	125	256	79	151	230
December	131	208	339	79	235	314
January	132	221	353	80	260	340
February	131	174	305	79	207	286
March	131	126	257	79	174	253
April	131	43	174	79	52	131
May	132	-	132	79	-	79
June	131	-	131	79	-	79
Totals	1,575	939	2,514	949	1,130	2,079

Assumptions:	Fort Benning	Fort Leonard Wood
Heating degree-days per year	2,400	4,800
Duration of "heating season"-months	5.5	5.5
Total fuels consumption-Billion Btu	2,514	2,079

Equation A-2 is valid for Forts Benning and Leonard Wood.

TABLE A-XV

SUMMARY OF EFFECT OF SEASONAL CLIMATE FACTORS ON FUELS DEMAND
FOR FIXED FACILITIES AT ARMY INSTALLATIONS IN UNURBANIZED LOCALITIES

		Btu Per 1,000 Btu of Fuel Consumed Per Year					
Heating Degree-Days Per Year	Approximate Duration of Heating Season Months per Year	Base Load*	Space Heating	Base Load* Per Month	Space-Heating Load-Coldest Month	Total Btu in Coldest Month	Ratio: Total Btu in Coldest Month to Base Load
1,000	3.5	801	199	67	56	123	1.8
2,000	4.5	668	332	56	89	145	2.6
3,000	5.5	573	427	48	94	142	3.0
4,000	5.5	502	498	42	110	152	3.6
5,000	6.5	446	554	37	116	153	4.1
6,000	7.5	402	598	33	120	153	4.6
7,000	8.0	365	635	30	121	151	5.0
8,000	8.0	335	665	28	126	154	5.5
9,000	8.5	310	690	26	124	150	5.8

Sources:

- Second column: based on data in Table 321 in the 1974 edition of the Statistical Abstract of the United States -- U. S. Department of Commerce.
- Third and Fourth columns: derived from the estimates in the second, third and fourth columns of Table A-XII.
- Fifth column: the third column divided by twelve.
- Sixth column: based on data in the reference for the second column and the estimates in the fourth column.
- Seventh column: the sum of the estimates in column five and six.
- Eighth column: estimates in the seventh column divided by estimates in the fifth.

***Base Load:** Mess halls, water heating and other housekeeping purposes which are not notably affected by season.

VI. REFERENCE LIST

1. Annual Summary of Operations - Facilities Engineering - Fiscal year 1971 - Office of the Chief of Engineers, Department of the Army.

2. Harold D. Hollis - Characterization of Energy Usage on Military Bases - U. S. Army Facilities Engineering Support Agency, Fort Belvoir, Virginia 22060, October 22, 1974.

3. Climatography of the United States No. 81 (by State) - U. S. Department of Commerce - National Climatic Center, Asheville, North Carolina, August 1973.

4. Anthony Von Nida - Nuclear Total Utility System for Military Installations - Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science, January 1974.

5. Meeting with Dr. Rigo at CERL, May 7, 1974.

6. Telephone conversation with Captain A. Von Nida, November 22, 1974.

APPENDIX B

MAJOR CHARACTERISTICS OF ENERGY PLANTATION FUELS PRODUCTION SYSTEMS AND THEIR EFFECTS ON THE TECHNICAL FEASIBILITY OF PRODUCING FUELS IN ENERGY PLANTATIONS FOR FIXED FACILITIES AT LARGE TROOP TRAINING CENTERS

I. INTRODUCTION

The first purpose of this appendix is to describe the major technical characteristics of Energy Plantations and the fuels-processing systems associated with them. The second is to compare these characteristics with the fuels-consumption profiles at large installations operated by the Army in unurbanized localities, and thereby to identify installations which, on the basis of technical considerations, are potential candidates for fuel derived from on-site or nearby Energy Plantations. Aspects of the fuels-consumption profiles at Army installations pertinent to this comparison are described in Appendix A. Capital and production costs and manpower requirements are not addressed in the comparison; their consideration is deferred to Appendices D, E, F and G.

The third purpose of this appendix is to describe in general terms plant species and cultural practices specially suited for Energy Plantation fuels-production systems. These descriptions are in the nature of a preamble to the more detailed discussion of Energy Plantations in Appendices C, F and G.

An Energy Plantation is a means for producing fuels by harnessing solar radiation in plants grown purposely for their fuel value on a large scale, using plant species and cultural practices selected to minimize the cost of the fuel produced. The harvest from the plantation might be used directly as a solid fuel, or it might be processed into some other fuel form. In any event, as long as the plants being grown in the plantation remain alive, they continue to store solar radiation for subsequent use. Therefore, an Energy Plantation collects <u>and</u> stores solar radiation for use when and as the need arises for fuel.

The availability of fuel, and hence of energy, from an Energy Plantation is not restricted to those times when the sun is shining. Moreover of the systems operable away from the seas and oceans for transforming sunshine directly or indirectly (through the wind and precipitation) into the forms of energy now derived from fossil and nuclear sources, only Energy Plantations and hydropower are naturally endowed with energy storage capability.

The circumstances under which Energy Plantations are a practical and inexhaustible source of energy are, however, not without bounds imposed by climate, topographic and a few other considerations. Generally speaking, Energy Plantations are a practical possibility for large Army installations in unurbanized localities in the region approximately defined by the eastern and central time zones but excluding the Appalachian foothills and mountain ranges. There are also a few suitable localities in California and Washington, but the major part of the mountain and Pacific time zones is not suitable. The localities at Forts Benning and Leonard Wood are suitable, although they are not among the best. Alaska is unsuitable for Energy Plantations. The major troop training centers in the United States which are in localities probably suitable for Energy Plantations are shown in Table B-I.

The plant material grown in Energy Plantations might be used as a solid fuel after partially drying it. Alternatively, it might be converted into a gaseous or liquid fuel by a pyrolytic or biological process. Consideration is given to these possibilities, and their relative merits and inherent feasibilities for troop training centers in terms of fuels storage, fuel yield from the plant-matter raw material, the overall thermal efficiency of the fuels conversion process and ready availability of alternate back-up fuels which could be substituted without having to modify equipment regularly fired with fuels produced from plant material grown in Energy Plantations. These evaluations are summarized in Table B-II. It is concluded that three fuel forms are worth consideration for production at troop training centers from plant material grown purposely for its fuel value. Firing the product of the plantation as a solid fuel is one of these. Another is to process the plant matter by flash pyrolysis under such conditions that a liquid fuel is produced in substantial yield. The third is to produce synthetic natural gas from the plant material by anaerobic fermentation.

In comparison with using plant material directly as a solid fuel, converting the plant material to synthetic fuel oil by pyrolysis does not appear to be a practical choice. Further analysis in the light of the existing patterns of fuel consumption and the classes of directly fired equipment in use at Army training centers indicates that conversion of plant material to synthetic natural gas is probably to be preferred over using it directly as a solid fuel, although the choice is not clear-cut at the level of analysis described in this and the preceding appendix. Detailed consideration of fuel forms has been confined, therefore, to production of synthetic natural gas and solid fuel from plant material grown in plantations at or near Army troop training centers.

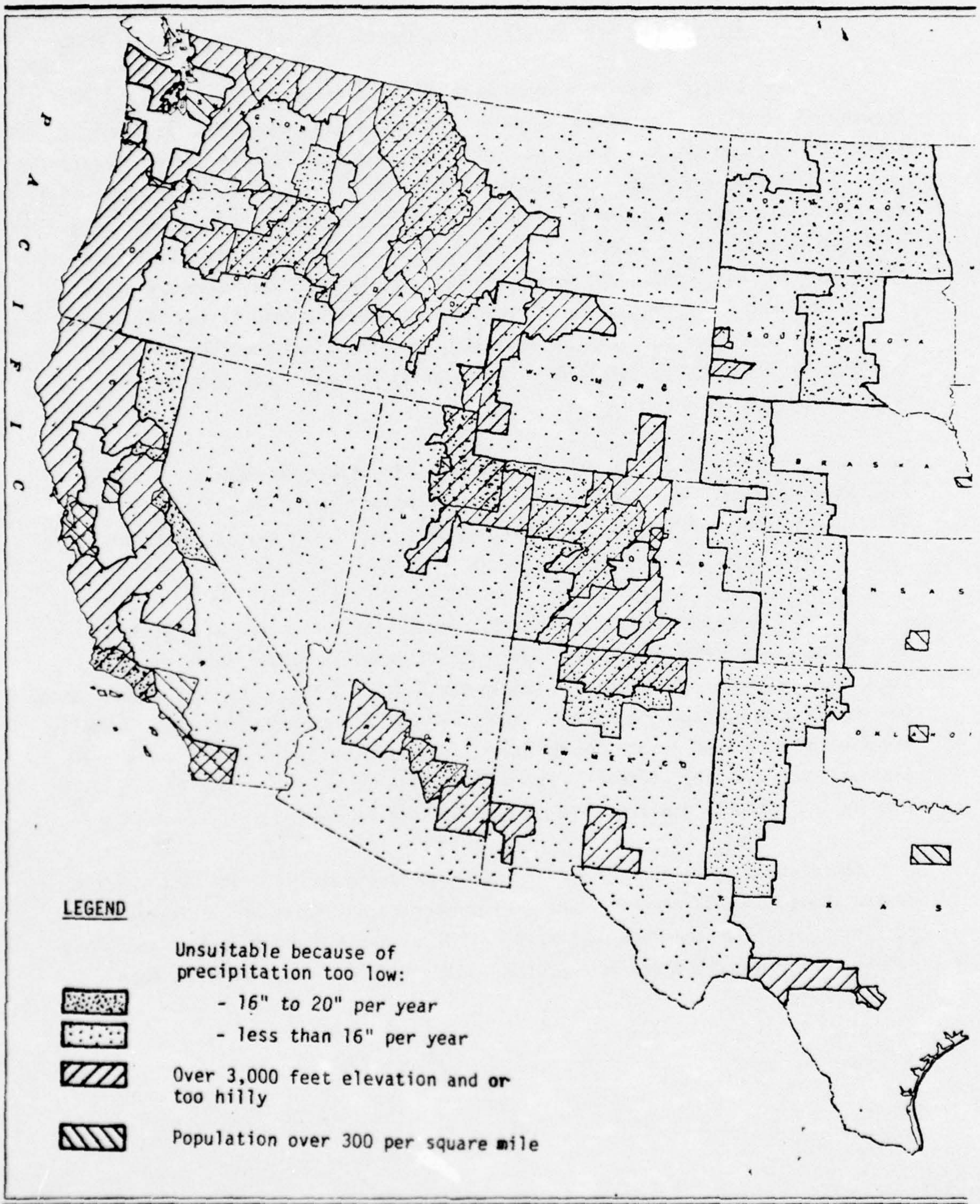
II. CLIMATE AND TOPOGRAPHIC CONSIDERATIONS

All plant species require a considerable amount of water to support their growth and survival. The amount of water required varies among species from somewhat less than two hundred to somewhat more than four hundred pounds of water per pound of oven-dry plant matter produced[1,2]. No plant species of interest for Energy Plantation culture requiring less than about two hundred pounds have been identified. In fact, many of the species of most interest require nearer three hundred than two hundred pounds per pound of harvestable, oven-dry plant matter produced. Moreover, to be of practical interest, a combination of plantation site and species must produce at least seven tons, and preferably nearer ten tons, of harvestable, oven-dry plant material per year (see particularly Appendices F and G).

The combined effect of the water and harvest yield requirements for Energy Plantation operation means that practical plantations cannot be established in territories where precipitation is normally less than about twenty inches per year.

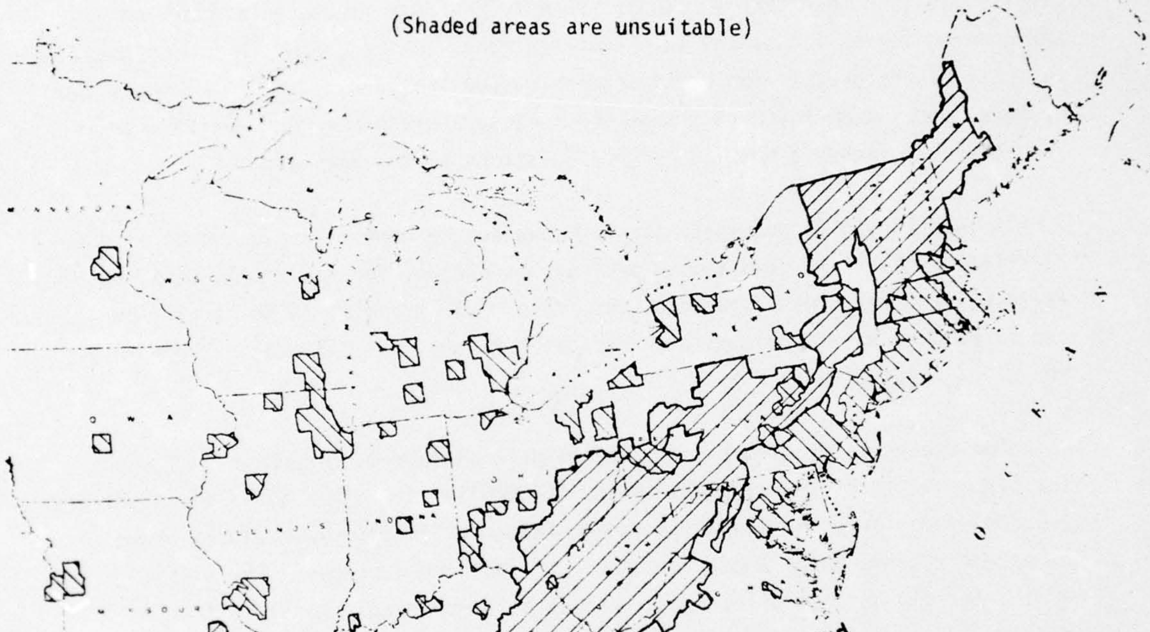
In the contiguous forty-eight states, precipitation is generally at least twenty inches per year in the territory east of about the 101st meridian and on the western slopes of the mountains along the Pacific coast. The land between these two regions, except for the western part of Idaho and eastern Washington, normally experiences less than twenty inches of precipitation per year and is therefore generally too arid for worthwhile Energy Plantation operation. This arid territory is indicated by the areas shaded with dots in Figure B-I.

Two degrees of relative aridness are shown in Figure B-I. The less densely dotted areas normally receive fewer than about sixteen inches of precipitation per annum, while in the more densely dotted areas between about sixteen and twenty inches of precipitation can be expected. This division in aridness has been


P A C I F I C
N E V A D A
W Y O M I N G
N E W M E X I C O
T E X A S
LEGEND
Unsuitable because of precipitation too low:
- 16" to 20" per year
- less than 16" per year
Over 3,000 feet elevation and or too hilly
Population over 300 per square mile

TERRITORY UNSUITABLE FOR ENERGY PLANTATIONS BECAUSE OF UNFAVORABLE PRECIPITATION AND OR TOPOGRAPHY AND POSSIBLY BECAUSE OF HIGH POPULATION DENSITY

(Shaded areas are unsuitable)



made because it is possible that in a few localities in the more densely dotted areas, Energy Plantations may be practically possible even though annual precipitation is less than twenty inches. Such is the case because rainfall during the growing season is usually more important than in the months when plants are dormant. Therefore, if the precipitation during the growing season averages two or more inches a month, even though the monthly average over the entire year is less than two inches a month, Energy Plantations may be feasible.

In Alaska, while precipitation is heavy in the coastal region south of the Aleutian range (ninety-two inches per year in Juneau, for instance), it is relatively low in many other parts of the state. For example, in Anchorage, Bethel and Fairbanks, normal precipitation is about twenty, sixteen and thirteen inches annually, respectively.

The steepness of slopes in the terrain is another factor which influences the practicality of Energy Plantations. Generally speaking, the field machinery required for plantation operation cannot be used effectively on slopes whose steepness exceeds about twenty-five percent (fifteen degrees). The elevation of the terrain is also a factor which must be considered. As elevation increases, productivity of land in terms of its ability to support plant growth generally declines, and at elevations over about 3,000 feet above sea level, productivity will be below that required for Energy Plantation operation.

The areas in Figure B-I shaded by crosshatching running diagonally from the lower left to the upper right are either too hilly, or at too high an elevation, or both for Energy Plantations. It will be seen that hilliness and high elevation rule out most of the land on the western slopes of the mountains along the Pacific coast, nearly all the land with more than twenty inches annual precipitation in Idaho and eastern Washington, and the land in the Appalachian region in the east.

The rate at which plants grow, assuming the water and fertilization materials supply and soil depth are not limiting factors, is dependent on the length of the growing season and on the hours of sunshine per day and ambient temperatures during the season. These factors are not expected to be a serious limitation on the feasibility of Energy Plantations in those regions in the contiguous forty-eight states where precipitation and altitude are within the acceptable ranges.

However, in Alaska the situation is quite different. The growing season is only three to four months long, mean summer temperatures rarely rise above about 60^{o} Fahrenheit, and where there is adequate rainfall and suitable land relief (absence of sharp hilliness, for instance), cloud cover substantially excludes the sun for considerably more than half the time it is above the horizon. As a consequence, total insolation during the growing season is much lower in Alaska than in the land between latitudes thirty-five and forty-five degrees north, for instance, in the forty-eight contiguous states (about 200,000 Btu per square foot in the growing season for Alaska versus about 370,000 for the intermediate latitudes in the contiguous states). The combination of low insolation, low summer temperature and short growing season leads to plant growth rates which are far too low for satisfactory Energy Plantation performance in Alaska. Incidentally, the climatic disadvantage in Alaska would be even more pronounced if the comparison were made between Alaska and the states further south than thirty-five degrees north latitude.

While neither a climate nor a topographic factor, it is convenient at this juncture to consider the possible effect of high population densities in the environs of Army installations on the feasibility of establishing Energy Plantations for meeting the fuel needs for fixed facilities at the installations. High population density in the general locale of a base would not necessarily be a consideration if sufficient land can be made available on the base itself for an Energy Plantation of suitable size. However, if enough land is not available on site, it may not be feasible to assemble sufficient nearby land off-site to meet the needs of an Energy Plantation for a base in a densely populated region. Consequently, those localities where population density exceeds three hundred persons per square mile have been identified in Figure B-I (areas shaded by crosshatching running diagonally from lower right to upper left). It will be seen that population density might preclude off-site Energy Plantations for Army installations to the east of the Appalachians from New Hampshire to northern Virginia, and in about fifty other widely separated localities to the east of the Rocky Mountains.

It is concluded after allowance for climate, topographic and population density considerations that Energy Plantations can reasonably be considered for major troop training centers and other large installations operated by the Army in unurbanized localities almost anywhere in the eastern and central time zones except for the Appalachian mountain area and the densely populated corridor extending along the Atlantic seaboard from northern Virginia to New Hampshire. Limited precipitation, adverse topography or high population density preclude most of the territory in the mountain and Pacific time zones from consideration. The local climate makes Army installations in Alaska unattractive possibilities for Energy Plantations.

In the light of these conclusions, fifteen of the twenty-two Army Installations shown in Table A-I are in localities technically suitable for consideration for Energy Plantations. The reasons for eliminating the others are shown in Table B-I.

TABLE B-I

TECHNICAL SUITABILITY OF SELECTED LARGE ARMY INSTALLATIONS AND THEIR ENVIRONS FOR ENERGY PLANTATIONS

Installation	Suitable	Probably Unsuitable and Reason Therefor
Fort Polk, La.	●	
Fort Hood, Texas	●	
Fort Stewart, Ga.	●	
FORT BENNING, GA.	●	
Fort Gordon, Ga.	●	
Fort Jackson, S. C.	●	
Fort Bliss, Texas		Low Precipitation
Fort McClellan, Ala.	●	
Fort Bragg, N. C.	●	
Fort Sill, Okla.	●	
Fort Huachuca, Ariz.		Low Precipitation
Fort Campbell, Ky.	●	
Fort Knox, Ky.	●	
FORT LEONARD WOOD, MO.	●	
Fort Dix, N. J.		Densely Populated Area
Fort Riley, Kans.	●	
Fort Lewis, Wash.	●	
Fort Carson, Colo.		Hilliness and Low Precipit
Camp Drum, N. Y.	●	
Fort Greely, Alaska		Climate Generally
Fort Richardson, Alaska		Climate Generally
Fort Wainwright, Alaska		Climate Generally

III. FINAL-FUEL-FORM CONSIDERATIONS

For reasons which will be explained in Section IV of this appendix, the plant material delivered from Energy Plantations will be either green plant matter, four or fewer years old, harvested from selected deciduous plant species and subsequently chipped in the field, or green clippings from selected warm-season grass species. The chips will be similar in shape and size to those produced by chippers used, for instance, by municipalities and utilities in the course of collecting and disposing of small wood and trimmings from trees. The grass clippings will be two to three inches long. In each case, the moisture content of the plant matter as it is delivered from the plantation will be of the order of half its gross weight, under which conditions its practically useful heating value, that is before condensing moisture in the products of its combustion, will be about four thousand Btu per pound of moist material.

The plant material harvested from an Energy Plantation might be used as a solid fuel. Or it might be converted into a gaseous or liquid fuel or a mixture of the two, with or without a simultaneously produced solid residue which might also have a useful fuel value. These possibilities are discussed briefly in the following subtitled sections.

Firing the Product of Energy Plantations Directly as a Solid Fuel:

Wood residues and bagasse are widely used for boiler fuel in the forest products and cane sugar industries, respectively. Corn cobs are also used for fuel at some canneries. Modern practice in larger installations is to feed these fuels from hoppers to fireboxes equipped with pneumatic spreaders and traveling grates. The boiler systems often have air preheaters, but economizers are not as prevalent. Use of the latter depends on the dew point of the flue gas produced from the fuel. If the fuel has been dried before firing to about thirty percent moisture or drier, economizers are now being recommended[4]. In any event, to achieve steady burning, the moisture content in the fuel must not be greater than about forty percent. At this upper limit for moisture, thirty percent excess air is recommended. However, if the moisture content of the fuel as fired is about thirty percent, excess air can be reduced to about twenty percent. With thirty percent excess air and about forty percent moisture in the fuel as fired, boiler efficiencies of about sixty percent can be achieved. The efficiency rises to about seventy-five percent with twenty percent excess air and about thirty percent moisture in the fuel as fired[4].

Boilers fired with wood chips or grass cuttings grown in Energy Plantations must be equipped with precipitators or other devices for controlling particulates air pollution. However, the ash which accumulates under the grate and in the particulates pollution control device on the stack will be returned to the Energy Plantation for its fertilizer value. The recovered ash will provide essentially all the fertilizer and trace elements, except fixed nitrogen, required for maintaining the productivity of the plantation. Recycling the ash in this way will also be a significant cost economy at the plantation.

Because the sulphur content of plant matter is generally less than one tenth of a percent by weight, boilers fired with wood chips or grass clippings will not need to be equipped with sulphur pollution control facilities. Moreover, no serious nitrogen oxide pollution problem is likely to arise when boilers of modern design for firing with plant matter are properly operated and maintained.

If the plant matter produced in the Energy Plantation is to be used directly as solid fuel, it will require at least partial drying before firing. Harvested material might be allowed to air-dry in fuel piles. However, if this practice were to be followed, precautions would need to be taken to prevent loss of fuel in the wind and spontaneous fire from localized overheating in the fuel pile. Carefully selecting the cross-section of fuel piles and their volume is one means for avoiding overheating. Another is to compact the pile at regular intervals.

A preferred way for partially drying the fuel is to expose it shortly before firing to a warm gas stream having a moisture content low enough to provide adequate drying. A rotary kiln might be used for this purpose. The warm gas stream might be flue gas from the boiler. Alternatively, part of the fuel might be burned specially to produce the warm gas stream. If this latter possibility were adopted, fines from the fuel might be used as the source of heat. In any event, whether flue gas is used or fuel is burned specifically for the warm gas stream, the exhaust from the fuel drier will probably have to be equipped with a particulates control device.

Neither vortex suspension nor fluidized bed burners are believed to be suitable for firing plant matter produced in Energy Plantations. For satisfactory performance in these types of burners, the moisture content of the fuel must be reduced to fifteen percent or less (air-dry or drier) and the particle size of the fuel as fired should not be greater than about a quarter inch, and preferably considerably smaller[5].

Modern boilers designed for firing wood residues and bagasse have turn-down ratios between three and four to one. However, such boilers respond far more slowly to changes in steam demand than do boilers fired with oil or gas[4,5].

Literally hundreds of boilers equipped for firing wood residues and bagasse are in use. Many of these boilers produce 100,000 pounds or more of steam per hour at 400 pounds per square inch and higher and at 700^{0} Fahrenheit and hotter. At least one bark-fired boiler has a steam rate of 250,000 pounds per hour at 1,500 pounds per square inch and 900^{0} Fahrenheit[6].

Modifying the Product of Energy Plantations by Pyrolysis:

Plant material, when heated above about 360^{0} Fahrenheit under conditions which prevent it from burning freely, produces a variety of gaseous, liquid and solid products. Some of these products have useful fuel value.

The relative amounts, composition and fuel value of the products of pyrolysis depend on a number of factors, among which are:

- the moisture content of the plant matter fed to the pyrolyzer;
- whether the heat required for pyrolysis is generated by burning some of the plant matter while it is in the pyrolysis vessel or whether the vessel is indirectly heated;
- the pyrolysis temperature;
- the residence time of the products of pyrolysis in the reaction vessel; and
- the configuration of the pyrolysis vessel.

Pyrolytic decomposition of plant matter has been studied by numerous people in the laboratory on many occasions in the most recent hundred years. Moreover, pyrolysis of plant matter has been practiced for centuries for making charcoal and wood tar with or without recovery of some of the many low molecular weight organics and other volatile materials simultaneously produced. Even these days, substantial quantities of wood charcoal are made, for instance, from native scrub hardwoods in Arkansas and from eucalyptus in Brazil. However, the procedures used in these operations tend to be based more on art than on science.

In recent years, considerable and increasing attention has been and is being given to production of fuels by pyrolysis from the organics in municipal waste and from residues of other origins. But as recently as October 1974, Kuester and Lutes[7] concluded pyrolysis process development

> "...is not well advanced....the first commercial scale plants just now coming on stream....design and operation of a pyrolysis process is somewhat of a speculative venture at the present time, with considerable confusion regarding vendor technical and economic claims."

The modern technology being developed for producing gaseous, liquid and solid fuels by pyrolysis of solid waste is, however, about the only basis for assessing the merit of pyrolytic techniques for converting the product of Energy Plantations into other fuel forms. Solid wastes, particularly those of residential origin, contain substantial quantities of cellulose, as will the harvested product from Energy Plantations. Residential waste is also likely to contain some plant matter (vegetable scraps, grass clippings and a little wood). However, there are also important differences between the organics in residential garbage and in the harvest from Energy Plantations. The former has little lignaceous material, whereas the latter may contain more than twenty percent by weight on a dry basis. The former generally contains a few percent of polymerized hydrocarbons, whereas the latter contains few hydrocarbons of any kind in consequential amounts.

The status of the technology for producing fuels from solid waste by pyrolysis has been critically summarized quite recently by Kuester and Lutes[7], and in less detail by Benham and Diebold[8].

It has been noted on page B-16 that the character of the products of pyrolysis of plant matter (and also of solid wastes) in terms of their usefulness as fuels depends on a variety of factors. Of these, the way in which the pyrolysis vessel is heated is the most influential. If the heat is generated in the vessel by partial combustion of the raw material fed to the vessel, the products of pyrolysis are water, a mixture of materials which are gases at normal ambient temperatures, and a solid residue. Little if any combustible material which is liquid at normal temperatures is produced. If air is used to support the partial combustion in the pyrolysis vessel, the heating value of the fuel gas will be between only about 150 and 170 Btu per standard cubic foot[8], whereas if oxygen is used, the heating value is still likely to be only about three hundred[7]. The combustible materials in the fuel gas are principally hydrogen and carbon monoxide, and the non-combustibles are nitrogen (if air is used in the pyrolyzer), carbon dioxide and water vapor.

Fuel gas having a heating value of three hundred Btu or less per standard cubic foot can only be used effectively in fired equipment designed for it. Consequently, the only back-up fuel supply which could be acceptable is an inventory of the fuel gas itself. But storing even as little as an annual average day's supply of gas having a heating value of three hundred Btu per standard cubic foot at Fort Benning (see Table A-VII), for instance, at six hundred pounds per square inch pressure would require a pressure vessel one hundred feet long and about eighty feet in diameter, or a spherical pressure vessel about one hundred feet in diameter. On a practical scale, providing storage facilities for fuel gas having a heating value in the range expected from a directly heated pyrolysis process is therefore clearly out of the question. Consequently, producing fuel gas by such a process from plant matter grown in an Energy Plantation for use in major troop training centers is not a practical approach.

It might be argued that low-Btu fuel gas of the type discussed in the previous paragraph could be stored underground in the same way that natural gas is on a large scale in many places throughout the nation. To be practical even for preliminary consideration, this approach would have merit only if suitable underground facilities were conveniently located with respect to major troop centers, and then only if the great mobility of hydrogen would not lead to unacceptable loss of heating value and gas volume by hydrogen diffusion into the strata surrounding the underground storage facility. While neither the availability of conveniently located underground storage capacity nor the conceivable fuel-loss problems caused by the high mobility of hydrogen has been investigated, it seems quite unlikely that underground storage is a practical consideration for low-Btu fuel gas produced by pyrolysis of harvest from Energy Plantations.

A char can also be produced along with the low-Btu fuel gas by a directly heated pyrolysis process. The amount produced and its heating value depend on how the process is operated. But since the low-Btu fuel gas inevitably produced while making the char is not an attractive fuel, there is no point to give consideration to the char either.

If the heat required for pyrolyzing the organic materials in solid wastes is generated outside the reactor, fuel gas having a heating value between about four and six hundred Btu per standard cubic foot is produced, along with varying amounts of char and, in one process at least, a notable volume of "fuel oil"[7,8]. The heating value of the char ranges from essentially zero up to about nine thousand Btu per pound, depending on the extent to which the organics in the feed are gasified. The "fuel oil" produced in the Garrett process has flow characteristics resembling No. 6 fuel oil and a heating value between ten and eleven thousand Btu per pound[7]. Presumably, somewhat similar pyrolysis products would be produced if the harvest from an Energy Plantation were used instead of solid waste as the pyrolysis raw material.

If the fuel gas produced by those indirectly heated pyrolysis processes which produce only fuel gas and char were used at troop training centers, operational awkwardnesses would arise which are similar to those noted earlier if the gas produced in directly fired pyrolyzers were used at the centers. Thus, the gas produced by indirectly heated pyrolysis can be used safely and effectively only in heaters equipped to handle it. Consequently, the only back-up fuel supply which could be acceptable is an inventory of the fuel gas itself. But the fuel is difficult to store--one annual average day's supply of gas having a heating value of six hundred Btu per standard cubic foot at Fort Benning, stored at six hundred pounds per square inch pressure would require a spherical pressure vessel about eighty feet in diameter. To provide adequate back-up storage would clearly be impractical. Consequently, converting plant material from the Energy Plantation primarily into fuel gas having a heating value in the intermediate range (400 to 600 Btu per standard cubic foot) is not a practical approach.

The indirectly heated pyrolysis process under development by Garrett Research and Development Company (sometimes referred to as the Occidental Petroleum Corporation process, because Garrett is a subsidiary of Occidental) can be operated on solid waste in such a way that a notable quantity of a liquid fuel resembling No. 6 fuel oil in its viscosity characteristics is produced[7]. A demonstration plant based on Garrett technology having a daily capacity of two hundred tons of organic matter derived from solid waste is being built by Procon, Inc., at El Cajon, California, with funds provided by Occidental, the United States Environmental Protection Agency and the County of San Diego. The facility, which is expected to be ready by the middle of 1976, will be operated by the county[9].

The relative quantities of fuel oil, fuel gas and char produced from solid waste by the Garrett process are strongly influenced by the pyrolysis temperature. It is reported on the basis of pilot plant operation, that if the residence time in the pyrolyzer is quite short (flash pyrolysis) and the pyrolysis temperature is around 900° Fahrenheit, between fifty and sixty percent of the fuel value in the solid waste is recovered in the fuel oil fraction[8,10], which as noted previously, has flow characteristics somewhat similar to those of No. 6 fuel oil. Char and fuel gas are also produced. If the pyrolysis temperature is between about 1400° and 1500° Fahrenheit, virtually no fuel oil or char is produced, the products of pyrolysis being essentially entirely fuel gas and an ash residue[8].

The composition of the fuel gas produced by the Garrett process is a function of pyrolysis temperature. It always contains hydrogen, carbon monoxide and dioxide, possibly some water vapor, and varying amounts of methane and higher-molecular-weight hydrocarbons, many of the latter being unsaturated. The average molecular weight, and hence also the boiling point, of the hydrocarbon mixture declines with increasing pyrolysis temperature[7]. Therefore, if fuel oil is the desired product from the Garrett process, a relatively low pyrolysis temperature should be maintained, possibly somewhat below 1000° Fahrenheit. The actual temperature at which the fuel oil yield is maximized is probably, however, a function of the composition of the organic matter being pyrolyzed. When municipal solid waste is the raw material, the optimum temperature appears to be about 900° Fahrenheit[7,8]. It is surmized that the optimum is likely to be somewhat higher when plant material from deciduous plant species is being pyrolyzed and somewhat less than 900° Fahrenheit when warm-season grass clippings are the raw material. The reported yield of fuel oil from a municipal solid waste in which the organics are about seventy-five percent of the oven-dry weight is the equivalent of roughly a barrel of crude oil (six million Btu more or less) per oven-dry ton of solid waste.

It is evident from the reports of pilot plant operation in the literature (see reference 7, for instance) that maximized production of fuel oil in the Garrett process depends on drying the organic raw material almost to oven-dryness and comminuting it to about twenty-eight mesh (twenty-three thousandth's of an inch) or finer before pyrolysis. The energy required for comminution is likely to be of the order of five horsepower-days per ton of plant matter processed.

If the Garrett process or another comparable with it were used for converting the harvest from Energy Plantations to a fuel oil, at least some of the energy required for drying the raw material and comminuting it, and for the heat required for pyrolysis, could be generated from the fuel gas and char produced during pyrolysis. Using these by-products in this way would avoid the operational awkwardnesses previously discussed for pyrolysis processess which produce only char and fuel gas having intermediate or low heating value. However, a rough energy balance suggests that the heating value in the char and fuel gas may not be quite sufficient to meet these energy requirements.

The Garrett process, or some other one having similar attributes, appears to offer the possibility of converting the product of Energy Plantations into a liquid fuel which presumably can be stored at least for some time, although probably not indefinitely because of the chemical unsaturation it is likely to contain. The solid residue resulting from the pyrolysis will contain essentially all the mineral matter and fertilizer material, except the fixed nitrogen, required for maintaining the productivity of the plantation. This material can therefore be disposed of conveniently and beneficially by recycling it to the plantation.

The thermal efficiency from harvested plant material to heat in steam, hot water or in air used for space heating for a process involving Garrett technology cannot be as high as is achievable by using the product of the Energy Plantation directly as a solid fuel. Such is the case because only fifty to sixty percent of the fuel value in the organic material pyrolyzed is converted to fuel oil[8,10]. Even if this fuel can be burned with a ninety percent efficiency, which is unlikely, the overall efficiency with which its heat is delivered to steam, for instance, can be only between about forty-five and fifty-four percent, whereas the corresponding efficiency, if the product of the Energy Plantation is used directly as solid fuel, is between sixty and seventy-five percent (see page B-14). A consequence of this difference in efficiencies is that a plantation to support a given heat load via the Garrett process will have to be between about ten and sixty percent larger, depending on the relative thermal efficiencies of the two processes, than that required for meeting the same load if the harvest of the plantation is used directly as solid fuel.

Another possible limitation to general use of fuel oil of the type produced by a Garrett process is its viscosity. For satisfactory firing, it must be preheated to about 250^{0} Fahrenheit.

<u>Producing Fuel Gas From the Product of Energy Plantations by Anaerobic Biological Reduction</u>:

It is well known that if plant matter is exposed to certain biological organisms in an anaerobic environment, the aliphatic materials, including the carbohydrates, in the plant matter are converted to a mixture consisting primarily of carbon dioxide, methane and water. The net effect of the biological digestion is a disproportionation of up to about ninety percent of the carbon in the aliphatic materials into a nonflammable substance (carbon dioxide) and into an excellent fuel (methane). In other words, some of the carbon in the aliphatic materials in the original plant matter is reduced to its lowest state of chemical reduction and another part of it along with some of the hydrogen in the aliphatics are oxidized to their highest states of chemical oxidation. That part of the carbon in the aliphatics which does not participate in the disproportionation either remains in undigested aliphatic material or finds its way into the structure of new biological organisms, which must be produced continuously to replace those which expire or are otherwise lost to the digestion process.

The materials in the plant matter which are substantially aromatic (lignin is one of these) or in which other true cyclic structures are an important part (the carbohydrates do not meet this latter criterion) are not noticeably digested by biological organisms under anaerobic conditions. This difference in susceptibility to anaerobic biological reduction depending on whether an organic material is substantially aliphatic or truly cyclic is a subject of discussion in Appendix D.

Anaerobic biological reduction proceeds most rapidly in the range from atmospheric to moderately above atmospheric pressure at temperatures between about 90^{o} and 150^{o} Fahrenheit. If the conditions under which the biological process is occurring are well regulated, it is estimated that between 4.4 and about 5.3 standard cubic feet of methane can be produced per pound of organic matter digested when the organic matter is derived from deciduous woody material. The estimated yield of methane is between 5.3 and about 6.3 standard cubic feet when grass clippings are the source of the organic matter (see Appendix D). The difference in methane yields between these two sources of organic matter is attributable directly to natural differences in their composition, and particularly to the difference in their lignin content.

The volume of carbon dioxide produced by the biological digestion is in the range between about equal to, to as little as two-thirds of, the volume of methane produced in well-regulated digesters.

The mixture of methane and carbon dioxide evolved from the anaerobic digestion reactor will be saturated with water vapor. If the mixture is dried, its heating value will be about 500 Btu per standard cubic foot. However, if the carbon dioxide and the water vapor are removed from the gas stream (well-established and widely used technology is available for this purpose), the resulting methane stream will not only have a heating value essentially equal to that of natural gas (about 1,000 Btu per standard cubic foot),but it will also be indistinguishable for all practical purposes from natural gas when used as a fuel.

While deliberate production of methane by anaerobic digestion of woody material or grass clippings is not known to be practiced anywhere these days, anaerobic digestion of various organic residues, with consequent generation of methane is. For instance, anaerobic digestion is used for stabilizing the organic material in sludges produced in a number of sewage treatment works in a variety of localities in the country. In some of these, the mixture of gases evolved containing the methane is flared--in others, it is used for fuel. A few stockyards and feedlots are anaerobically digesting manure as a step in its control and disposition, and as a means for recovering fuel value from it without first having to dry it. Also, as is well known, plant residues and other organics which find their way into the depths of many natural lakes and ponds are digested anaerobically with evolution of marsh gas, a popular name for methane. It is concluded, in the light of these applications of anaerobic digestion which lead to evolution of methane, that methane can probably be produced in high yield in a practical way from grass clippings and from woody matter from selected deciduous species,providing these materials have been rendered readily accessible to the necessary biological organisms by suitable physical pretreatment. This conclusion is substantiated in considerable detail in Appendix D.

Assuming the validity of this conclusion and that the costs of producing a substitute for natural gas by anaerobic digestion of plant material are tolerable, the fuel so produced is likely to be attractive to troop training centers, and especially to those which rely heavily these days on natural gas. Synthetic natural gas produced in this way can be used interchangeably with natural gas in equipment suitable for the latter. That means that for such equipment, natural gas is a satisfactory back-up fuel for the gas produced from the harvest of the Energy Plantation. It also means, in principal at least, that existing natural-gas storage facilities can be used to store temporarily synthetic natural gas produced from the product of the Energy Plantation. For this purpose, the gas produced in the biological digestion facility will have to be compressed to pipeline transmission pressure (about 1000 pounds per square inch) and then be injected into the gas transmission system through appropriate flow meters.

The spent sludge from a biological synthetic-natural-gas production facility will be an essentially complete source of fertilizer, trace minerals and other factors which must be returned to the plantation in order to maintain its productivity. Thus,recycling the spent sludge to the plantation will have a beneficial effect for plantation operation and provide the means for sludge disposition.

The thermal efficiency from harvested plant material to heat in steam or hot water,or in air used for space heating for a process involving synthetic natural gas produced by anaerobic digestion cannot be quite as high as is achievable by using the product of an Energy Plantation directly as solid fuel. It is estimated (see Appendix D) that the overall thermal efficiency of producing synthetic natural gas from plant material derived from deciduous species is about fifty-five percent. From warm-season grass material, the corresponding efficiency is about sixty-three percent. These overall efficiency estimates are based on the sum of the heating value in the plant matter used as raw material for gas production and the original fuel equivalent of the energy inputs required to operate the gas production process. If it is assumed that the gas can be burned in a heater with ninety percent thermal efficiency, an admittedly optimistic assumption, the overall efficiency with which heating value can be transferred from plant matter to steam, hot water or air via synthetic natural gas is about fifty percent in the case of deciduous woody material and fifty-seven percent from warm-season grass matter. The corresponding efficiency with which the fuel value in the product of Energy Plantations, if directly fired as solid fuel, can be so transferred is between about sixty and seventy-five percent. A consequence of these differences in overall efficiency is that the plantation required to support a given heat load will be between about twenty and fifty percent larger if deciduous plant matter is grown and first converted to synthetic natural gas, than if the plant matter is fired directly as solid fuel. If a warm-season grass is produced in the plantation, the difference in plantation size for gas production versus solid-fuel production is between about five and thirty percent. These comparisons in plantation area requirements assume that the plantation provides the raw material for gas production and the fuel required for operating the gas production process.

Enzymatic Conversion of Polysaccharides in Plant Matter to Simple Sugars:

Enzymatic inversion of cellulose to simple sugars has been and is being given intense attention these days, particularly by Spano and his associates [11]. The process involves using part of a substrate containing cellulose to generate, by aerobic biological means, an aqueous solution rich in enzymes which hydrolyze polyhexoses (cellulose is one of these) to simple water-soluble sugars. The remainder of the substrate is then exposed to this enzyme-rich liquor under conditions which promote relatively rapid inversion of its polyhexoses. The resulting sugars, while still in solution, could then be fermented anaerobically either to methane and carbon dioxide or to ethyl alcohol and carbon dioxide by well-known technology.

Thus, enzymatic conversion of cellulose and other polyhexoses into simple sugars might be a step in a process for producing synthetic natural gas or a volatile liquid fuel (ethyl alcohol) from plant matter grown in Energy Plantations. Because of these final fuel form possibilities, it is appropriate to evaluate processes involving an enzyme treatment step for converting the harvest from Energy Plantations into other fuel forms. Two possibilities must be considered in the evaluation--namely, production of synthetic natural gas and of ethyl alcohol.

Enzymatic Conversion of Polysaccharides in Plant Matter to Simple Sugars and Thence to Synthetic Natural Gas:

The merit of making synthetic natural gas for use in troop training centers has already been described. The relative merit of making it by a process involving a separate enzyme production step ("Spano technology") versus a process using direct anaerobic digestion without Spano technology depends primarily on:

- the relative energy conversion efficiencies;
- the relative yields of methane;
- the relative rates at which methane is produced, and hence the relative physical sizes of the production facilities required, and
- the relative capital and production costs associated with the two processes.

For both processes, the raw material must be comminuted to a fine particle size before being treated biologically. In the case of the process not involving a separate enzyme treatment step, it is estimated that the raw material must be ground to about forty mesh, whereas in the work reported by Spano, et al., for the process with a separate enzyme treatment step, the raw material appears to have been ball milled to a considerably finer particle size, 270 mesh being mentioned for one particular substrate[11]. The grinding energy required for the latter process will, therefore, probably be greater than that estimated to be needed for the former and as a consequence, tend to make the overall energy balance less favorable.

In any event, the energy expended for grinding will be substantial in either process. In the process without a separate enzyme treatment step, for instance, it is estimated that about three million Btu as original fuel will be required to provide the grinding energy per air-dry ton of raw material processed for gas production. This original fuel requirement for grinding accounts for about eighteen percent of all the energy, expressed as original fuel value, delivered to the process as raw material, mechanical energy and process heat (see Appendix D).

Although information is not available with which to estimate the methane yield from the process involving Spano technology, it is possible to adduce that its methane yield cannot be greater and probably must be less than the methane yield from the process involving direct anaerobic digestion.

The methane yield from a process based on Spano technology cannot be greater than that from one depending solely on direct anaerobic digestion, because more oxygen is involved. The additional oxygen is required by and introduced in the aerobic step (enzyme generation) in the process incorporating Spano technology. This additional oxygen can leave the system only in combination with carbon. Thus, since the same plant matter would be used in either process, and since the plant matter is the only source of carbon for the processes, there is necessarily less carbon available per unit weight of plant matter processed for methane production when Spano technology is used. Incidentally, when comparable substrates are subjected to Spano technology and to direct anaerobic digestion, the experimental evidence available[11,12] indicates rather conclusively that the organic matter in the substrate can be consumed to the same degree by either process.

Even though the reasoning in the preceding paragraph leads inevitably to the conclusion that the methane produced per unit weight of organic matter consumed by a process using Spano technology must be less than by a process relying solely on anaerobic digestion, the data available with respect to the Spano technology are not sufficient for estimating how much less. Specifically, data are lacking for determining the fraction of the plant matter fed to the process which must be made available to the aerobic enzyme generation step. It seems likely, however, that this fraction may have to be fairly substantial if the polysaccharide inversion step is to proceed at a practical rate in a continuous process for making methane. It is quite probable, therefore, that the volume of methane produced by Spano technology will be notably smaller than that produced by direct anaerobic digestion. The plantation required for a given methane production requirement will therefore have to be larger if Spano technology is used.

It is conceivable that the rate at which plant matter is digested to methane by Spano technology may be somewhat faster than the rate at which it is produced by direct anaerobic digestion. It is estimated for the latter case that digestion of about ninety-three percent of the digestible material in the plant matter fed to the process will require an average retention time of about fifteen days in a continuously operated anaerobic digester (see Appendix D). This retention time is two or three times the washout time for the particular biological system involved.

The washout time for continuous anaerobic digestion to methane of a feed produced by Spano technology is also likely to be about five to seven days. Thus, for safe practical operation of such a biological system, the average retention time in the digester is likely to be set at seven to nine days, or longer if insufficient digestion occurs in that time. Data on the rate at which polysaccharides are inverted to simple sugars by Spano technology indicate that a reaction time of at least two days is required in batch inverters[11]. Therefore, a somewhat longer retention time will be required if the inverter is run continuously. The total retention time required for inversion and methane generation by Spano technology in a continuous process is therefore not likely to be less than ten to twelve days. If this total retention time is actually three to five days shorter than that required for direct anaerobic digestion, the cost of the inverter and digester may be less than the cost of the digester required for a direct anaerobic digestion process.

Overall, however, the process train for the Spano process will be more complex than that required for direct anaerobic digestion because the former will require facilities for enzyme production. This greater complexity will tend to make the cost of a system based on Spano technology more expensive than a less complex process based on direct anaerobic digestion. The grinding equipment for the Spano process will almost certainly have to have greater capacity than that required for a direct anaerobic process. However, the facilities for removing carbon dioxide and water vapor from the gas mixture evolved from the anerobic digester will be similar for the two processes. The net effect of the various differences in process steps and equipment capacities between a Spano system and a direct anaerobic system on the overall cost of a synthetic-natural-gas production facility cannot be estimated realistically at present because of uncertainties with regard to the Spano process. However, it seems that at equal SNG production capacity, the cost of a Spano facility is more likely to be higher than lower than the cost of a facility in which direct anaerobic digestion is used. Coupling this conclusion with the probability that the Spano process will have a lower thermal efficiency and a lower methane yield per unit weight of plant matter processed, leads to the conclusion that direct anaerobic digestion is almost certainly to be preferred over Spano technology for making synthetic natural gas at troop training centers from the harvest of Energy Plantations.

Enzymatic Conversion of Polysaccharides in Plant Matter to Simple Sugars and Thence to Ethyl Alcohol:

The relative merit of a process involving Spano technology producing ethyl alcohol versus direct anaerobic digestion producing synthetic natural gas,or direct use of the product of Energy Plantations as a solid fuel depends primarily on the relative yields of energy in the final fuel forms and the advantage of having ethyl alcohol available at troop training centers for use as a liquid fuel which will not require preheating before it is fired.

Based on information in the literature on the yield of ethyl alcohol from waste paper, an estimate can be made of the yield of ethyl alcohol from woody plant material. In terms of the energy content of the product, a Spano process producing energy in the form of ethyl alcohol from woody plant material will yield about five million Btu (fifty-five to sixty gallons) per oven-dry ton. A direct anaerobic digestion process producing synthetic natural gas from deciduous woody plant material is expected to yield between about nine and 10.7 million Btu per oven-dry ton,and direct use of the plant matter from the plantation will yield a useful heating value of nearly twelve million Btu per oven-dry ton. For the ethyl alcohol process then, the Energy Plantation for ethanol production will have to be at least 1.8 times as large as that required for methane production for the same energy output assuming the consumption efficiency of the two fuels is also the same. One substantial reason for the low yield of energy in the ethyl alcohol process is that the five-carbon hemicelluloses in the plant material are not utilized because they are unfermentable to ethyl alcohol. In addition, the Spano process producing ethyl alcohol will have some of the same disadvantages as the Spano process producing synthetic natural gas.

It is concluded that desirable as having alcohol as a fuel at Army training centers may be, the low yield with which it can be produced from plant matter makes producing it from Energy Plantations an impractical proposition.

* * * * * *

The more important guiding conclusions reached in the preceding analysis of the various final fuel forms which conceivably might be produced at Army troop training centers from plant material grown in Energy Plantations are summarized in Table B-II.

TABLE B-II

SUMMARY OF FINAL-FORM CONSIDERATIONS

Final Fuel Form	Conversion Process	Heating Value - Percent of Heating Value of Air-Dry Plant Matter**	Relative Plantation Area Required	Major Disadvantages S=Serious T=Tolerable	Candidate For Troop Training Centers
Solid	None-	100	1.0	Needs partial drying-(T) & airborne particulates control-(T)	Yes
Fuel Gas	Pyrolysis-directly heated	less than 100	more than 1.0	Heating value (150 to 300 Btu per SCF*)-(S), No back-up fuel-(S), Storage problem-(S)	No
Fuel Gas	Pyrolysis-indirectly heated, high temperature (over 1400°F)	less than 100	more than 1.0	Heating value (400 to 600 Btu per SCF*)-(S), No back-up fuel-(S), Storage problem-(S)	No
Fuel Oil	Pyrolysis-indirectly heated, intermediate temperature (~900° to ~1000°F)	50 to 60	1.1 to 1.6	Requires heating before firing-(T), Possible poor shelf life-(T)	Yes
Synthetic Natural Gas	Anaerobic Digestion	65 to 85 (woody raw material) 60 to 70 Grassy raw material)	1.2 to 1.5 (woody raw material) 1.1 to 1.3 (grassy raw material)	Storage problem-(T)	Yes
Synthetic Natural Gas	Spano Technology	less than for direct anaerobic digestion	Larger than for direct anaerobic digestion	Probably lower CH_4 yield and higher costs than for direct anaerobic digestion-(S)	No
Ethyl Alcohol	Spano Technology	40 to 45	2 to 2.7	Low alcohol yield from plant matter-(S)	No

* SCF = Standard Cubic Foot - at 60° Fahrenheit and one atmosphere.

** Entries in this column are heating value of the indicated fuel as a percentage of the heating value of the air-dry plant matter directly used for producing the indicated fuel--the entries do not take account of the fuel required to provide the mechanical energy and heat required to operate the conversion process.

IV. INFLUENCE OF FUELS-CONSUMPTION PROFILES AT TROOP TRAINING CENTERS

The analysis in Appendix A of fuels requirements these days for fixed installations at major troop training centers in unurbanized areas indicates that:

- practically no solid fuel is used (see tables A-VI, A-VII, and A-VIII);
- at centers in the south, gas is the major source of heat by a wide margin (see tables A-VI and A-VII);
- at centers further north, fuel oil becomes an increasingly important source of heat as geographic latitude increases (see tables A-VI and A-VIII);
- at nearly all centers, half or more of the fuels consumed, when expressed in terms of total heating value, is used by heaters having heat production capacities smaller than 3.5 million Btu per hour, and in about two-thirds of the centers, in heaters having heat production capacities smaller than 750,000 Btu per hour (see tables A-III, A-IV, A-VII and A-VIII); and that
- the vast majority of heaters at most training centers consists of directly fired units having heat production capacities less than 750,000 Btu per hour (see Table V-A).

These facts have crucial bearing on selection of the appropriate fuel form for training center use to be produced from the output of Energy Plantations.

Solid fuel of any kind, for instance, cannot be used very effectively in small-capacity unattended heaters. Moreover, even the few large-capacity central heating plants now in use at training centers would require considerable revamping, and possible replacement, to make them satisfactory for solid fuel, because most of them are equipped for gas or oil and therefore have neither grates in their fireboxes nor particulates control devices on their stacks.

It is concluded that solid fuel from Energy Plantations is likely to be acceptable as a major heat source at most troop training centers only if:

- the many (often thousands) small-capacity heaters currently in use at the centers are replaced by steam or pressurized hot-water heat distribution and delivery systems supplied from large-capacity central heating plants designed for solid fuel, and the existing larger-capacity heaters and central-heating facilities are converted from oil or gas to solid fuel, or if
- all existing heaters in buildings are replaced by electric resistance heaters supplied with electricity from large central thermal-electric plants fired with solid fuel from the Energy Plantation.

The first of these choices would be rather costly. At Fort Benning, the cost is estimated to be more than thirty million dollars, and at Fort Leonard Wood to be more than twenty-three million (see Appendix E). These conversion costs are several million dollars greater than the anticipated costs of converting these bases to synthetic natural gas produced from plant material grown in plantations at, or in the vicinity of, the bases.

The second choice (conversion to electric heating) is likely to be more costly than converting the bases to solid fuel from Energy Plantations. It would involve installation of central boilers equipped for solid fuel, electricity generation, distribution and control systems, and total replacement of the heaters presently in use. Moreover, the Energy Plantation required to support an electric heating system would have to be 2.5 to three times as large as that required for the first choice, because of the poor thermal efficiency (not over about forty percent) necessarily encountered when heat is produced from electricity produced in a thermal-electric station. Electric heating has therefore been discarded from consideration.

It is conceivable that a combination of electrical and central steam or hot-water heating might be a practical approach. For this possibility, steam produced at high pressure and temperature from solid plantation fuel would be used to drive back-pressure turbo-generator sets. The steam at lower pressure and temperature exhausted from the turbines would then be used for space and water heating. The exhaust steam might be used in the buildings nearer to the turbo-electric station, thereby economizing the cost of steam distribution and hot-condensate recovery systems. Electric heating would be installed in buildings more remote from the turbo-electric station. The feasibility of this possibility is likely to depend on the physical arrangement of buildings requiring heat at each training center. It has not been investigated for any center.

Fuel oil produced by "flash" pyrolysis in indirectly heated pyrolyzers operated at about 1000° Fahrenheit may be entirely satisfactory for the oil-fired central heating plants in use in some Army bases. But these plants, except in Alaska which is unsuitable for plantations, account for considerably less than half of the total fuel consumption at most training centers in the lower forty-eight states.

Pyrolysis fuel oil, because it must be preheated before firing (it is reported to have a temperature-viscosity relationship similar to that of No. 6 fuel oil), would be troublesome to use in the extremely numerous small-capacity heaters at most Army bases. Substitution of the small heaters by a few large oil-fired central heating plants, and conversion of the bases which rely heavily on gas to fuel oil, would be necessary if pyrolysis fuel oil is to become the principal source of heat at Army training centers.

Pyrolysis fuel oil appears likely, therefore, to be less satisfactory than conversion of Army training centers to solid fuel produced in plantations because it would involve:

- installation of central-station heating plants and steam or hot-water distribution and hot-condensate recovery systems similar in many respects to those which would be required if solid fuel produced in energy plantations were to be used,
- installation of pyrolysis facilities with particulates air pollution and water pollution control (capital cost about twenty million dollars at Fort Benning or Fort Leonard Wood), and
- a larger plantation for a given heat load than would be required if solid fuel were to be used (see Table B-II).

Boilers equipped for firing pyrolysis fuel oil at either Fort Benning or Fort Leonard Wood are likely to cost about four million dollars less than the corresponding boilers equipped for solid fuel from plantations. This cost saving would offset part of the cost of pyrolysis facilities. Also some economy may be possible in the cost of the steam or hot-water distribution and hot-condensate recovery systems if pyrolysis fuel oil is used rather that solid fuel in central heating plants because, since oil is easier to fire than solid fuel, numerous smaller-capacity district heating plants may be feasible with pyrolysis oil in place of fewer larger-capacity plants if solid fuel were burned. However, this additional economy possibly arising from use of pyrolysis fuel oil is likely to amount to only two or three million dollars in the cost of facilities for either Fort Benning or Fort Leonard Wood.

It must be concluded, therefore, that the cost of facilities and their operation for producing pyrolysis fuel oil from plant material grown in plantations and for using it at Army training centers will be considerably greater than for the corresponding facilities and operation for using the plant material directly as a solid fuel. For this reason, pyrolysis fuel oil has been eliminated from consideration.

Synthetic natural gas produced from plant material could be used without major alteration to the heating systems in most training centers in the south and in many others where considerable quantities of gas are presently used. Moreover, it would be a direct substitute for the fuel likely to face the greatest curtailment in supply in the next few years. Oil-fired equipment can be modified to use it fairly easily and relatively inexpensively, although gas distribution systems might have to be extended at some training bases and installed from scratch in others. However, gas distribution requires a "one-pipe" system (the equivalent of a hot-condensate return line is not required) and gas pipe does not require thermal insulation. Gas distribution facilities would, therefore, be far less expensive to extend or install than would the piping required for a steam or hot-water distribution system.

Conversion of plant material grown in plantations into synthetic natural gas for use at troop training centers clearly has advantages over using the plant material directly as a solid fuel at the centers. The advantages are:

- relatively minor changes will be required in the heating systems presently in use at most large training centers to make them suitable for synthetic natural gas, whereas rather drastic changes will be required to make them suitable for solid fuel;
- because synthetic natural gas is interchangeable in performance with natural gas, its use can be phased in without serious dislocation at centers whereas conversion to solid fuel would pose far more complex introduction problems;
- because gas-fired heaters are more easily controlled than is equipment which uses solid fuel, greater economy in fuel consumption can be achieved with the former than the latter;
- because synthetic natural gas is a clean-burning fuel, air pollution control devices are not required where it is used, whereas particulates air pollution control devices will be required for equipment in which solid fuel is used; and
- fixed nitrogen in plant material is expected to be conserved by the synthetic-natural-gas production process in a form in which it can be recycled to the plantation, whereas fixed nitrogen is lost when plant material is consumed as a solid fuel--fixed nitrogen is expensive and the relationship between its supply and the demand for it can be expected to become increasingly tight in the future.

At first sight, it may appear that fuel inventory would be easier to manage if plant matter from a plantation is used as a solid fuel rather than as raw material for synthetic natural gas. But such is probably not the case. It is well known that the operating rate in biological processes usually cannot be changed very rapidly or frequently without seriously and protractedly upsetting the biological system involved. This means that if synthetic natural gas is the fuel produced from the plantation, the main inventory will have to be synthetic natural gas, which fortunately is stable when properly stored. It is conceivable that arrangements can be made to store temporarily surplus gas in storage facilities regularly used by the natural-gas industry. This possibility, however, has not been discussed with the industry.

If plantation-grown plant material were to be used directly as a solid fuel, inventory could, in principal at least, be maintained either as unharvested plant material or as harvested material held in storage. Neither of these approaches, however, would be very satisfactory. The plantation operation will be field-machinery intensive, and consequently, maintaining an acceptable equipment cost, and hence cost of plant material produced, depends on making steady use of the machinery.

Harvested plant material is biologically unstable. Unless its moisture content is reduced to about air-dryness before protracted storage (several weeks, for instance), it degrades with loss of fuel value quite rapidly by

- oxidation if air has access to it, or by
- anaerobic reduction to methane and carbon dioxide (which escape) and water if air is excluded from it.

In either event, pollution problems could ensue also.

Having regard for all factors pro and con between using plant material as solid fuel or as raw material for synthetic-natural-gas production, it seems likely that the latter use is to be preferred, providing the cost of the SNG is acceptable, and especially if a program with the gas industry can be worked out for temporary storage of surplus SNG.

V. SELECTION OF PLANT SPECIES AND CULTURAL PRACTICES FOR ENERGY PLANTATIONS

Previous work[13] has indicated that the species grown in Energy Plantations must be perennials, so that harvesting can take place continuously throughout the year in response to the demand for solid fuel or for raw material from which to make synthetic natural gas by anaerobic fermentation. The importance of limiting consideration to perennial species is not dependent, however, only on the demand for solid fuel or raw material for synthetic natural gas.

If annual species were produced in the plantation, they would, in all probability, have to be started in a short interval in the spring and be harvested, also in a short interval, in the fall while they are still upright and relatively easy to reap. In any event, they would have to have been completely harvested by the time the land must be prepared in the spring for the next planting. Under such a seeding and harvesting schedule, plantation machinery would have to be provided for peak activity rates, and it would be relatively idle at other times. More field machinery would obviously be required to meet such a production schedule than to meet the more even schedule throughout the year which culture of perennial species makes possible.

Moreover, storing harvested plant matter from annuals for use between harvests would be a horrendous problem. Green plant matter gradually develops considerable biological activity beginning within a few days after it is harvested and lasting for at least several weeks if steps are not taken to arrest or prevent the activity. As noted earlier, biological activity in harvested plant matter reduces its fuel value as a solid fuel and as a raw material for SNG production. The activity can be arrested by drying the plant matter to an air-dry condition shortly after the harvest. It can also be controlled and even prevented with bactericides and other preservatives. Air-drying could be relatively costly and might require considerable fuel (cf. the fuel needs for crop-drying in the small-cereals and corn belts, for instance). Reliance on bacterocides and the like would not only be costly, but their presence in the plant matter would interfere with its subsequent use for SNG production by anaerobic reduction.

The preservation of perennial plant material is far simpler. Nature preserves it until it is harvested as long as the plant is alive, and it can be reaped more or less continuously throughout the year only a few days, and certainly not more than a week or two, before it is needed as fuel or as raw material for SNG.

Not all perennials are equally suitable for SNG production, although there are fewer limitations on species suitable for solid fuel. Lignin, for example, is not converted to methane by anaerobic digestion. Therefore, species having relatively low lignin contents such as grasses and deciduous tree species are to be preferred over conifers if SNG is to be made from the plant material.

Moreover, sapwood in woody species appears to react more rapidly in biological systems than does heartwood. Lumber, for instance, is downgraded if it contains sapwood. As a consequence, if a woody species is to be the source of plant matter for methane production, a species which grows rapidly in its first few years before it has a chance to develop much heartwood is to be preferred over one which grows more slowly. Certain deciduous species have this trait. Conifers generally do not. This factor is a second reason why conifers are not indicated for SNG plantations, whereas certain deciduous species are. A species which grows rapidly during its first few years is also advantageous if its plant matter is to be used as a solid fuel.

A substantial number of deciduous species, especially when they are not more than four or five years old, will sprout vigorously from their stumps after their structure above ground has been harvested. It is a matter of established fact that many deciduous species can be harvested at least five or six times before the vigor with which they regrow begins to wane. Since planting costs are a substantial part of the costs of producing any plant matter, those deciduous species which sprout readily after harvesting and, hence, provide several crops per planting have an advantage over other species which do not. Conifers rarely sprout after they have been cut down, which is another reason why certain deciduous species are to be preferred over conifers as a source of plant matter for SNG production or solid fuel.

Deciduous species which grow rapidly when they are young and sprout vigorously from their stumps after harvesting usually can also be started vegetatively from clones. A clone is a live stick four to twenty inches long (the length depends on the species) cut from a living plant. If the clone is stored in a moist condition in a cool place (between forty and fifty degrees Fahrenheit) for two or three months and then is stuck in the ground, it will start growing rapidly soon thereafter. This is another trait not shared by conifers. The advantages of vegetative reproduction over reproduction from seeds for Energy Plantation culture are:

- it is far easier and cheaper to collect clones than seeds from tree species; and
- clones reproduce a plant genetically identical with the one from which they were cut, whereas seeds may not, be cause the plant they produce depends on the origin of the pollen involved in seed formation.

Fortunately, there are a number of well-known deciduous tree species which reproduce vegetatively, resprout copiously from their stumps several times without loss of vigor, grow relatively rapidly when they are young, and develop little heartwood until their structure above ground is four or five years old. Some of these species are hybrids developed for propagation in a wide variety of soil types and climates. Others are natural species which adapt themselves fairly readily to a range of soils and climates. A representative list of these species and where they have been grown well under plantation-type conditions is shown in Table B-III. Some yield data are available for all the species at the sites indicated by an "X" in the table. For those sites indicated by an "O", sufficient yield data are available for predicting yields under various combinations of planting density and harvest schedule. The important conclusion to draw from Table B-III is that there is at least one deciduous species which is known to grow well under plantation-type conditions, essentially everywhere in the lower forty-eight states where establishing Energy Plantations may be of interest to the Department of Defense.

The average yield per year per acre which can be produced from deciduous species of the types shown in Table B-III in localities to which they are well suited, depends on the number of plants per acre and the harvest schedule. Characteristically, the yields are maximized when the planting densities are between about 5,000 and 11,000 plants per acre (a cornfield has between 20,000 and 28,000 stalks per acre), and the harvest schedule consists of a first harvest when the planting is one year old followed by five to seven additional harvests at two to four-year intervals thereafter. Generally speaking, higher planting densities and longer periods between harvests are indicated for more northerly latitudes, although there is room for considerable flexibility in these matters.

TABLE B-III

A REPRESENTATIVE LIST OF DECIDUOUS SPECIES WHICH SHOW PROMISE FOR PLANTATION CULTURE AND LOCALITIES WHERE THEY HAVE GROWN WELL IN MANAGED PLANTINGS

Locality	Hybrid Poplars													
	NE 388, 49 and 252	Others	Aspen & hybrids	Black Cottonwood	Red Alder	Sycamore	Pin Cherry	Plains Cottonwood	Eastern Cottonwood	Silver Maple	European Black Alder	Green Ash	Sweetgum	Eucalyptus
New Hampshire			X				X							
Wisconsin		X	X											
Minnesota			X											
North Dakota								X						
Washington		X		X	X									
Pennsylvania	O	X												
Ohio											X			
Indiana									X					
Illinois									X		X			
Nebraska									X					
Kansas								O	X	O		X		
Georgia						O						X	X	X
Alabama									X		X		X	
Mississippi						X			O					
Louisiana									X					
Texas									X					
Florida														X

Using the growth simulation model developed in InterTechnology (see Appendix C) and actual yield data, estimates have been made of the maximum annual yields per acre which can be expected from eight representative deciduous tree species grown under plantation conditions at various widely separated sites. These estimates are summarized in Table B-IV. The conclusion to be drawn from the estimates shown in this table is that by properly selecting the species, an average annual yield of between eight and nine oven-dry tons of plant matter probably can be harvested widely in the eastern and central time zones in the United States.

Certain perennial grasses are also promising sources of raw material for SNG production and for use for solid fuel. There are two broad categories of grasses which grow widely in the United States--the so-called cool-season grasses and the warm-season grasses. The cool-season grasses are frost-resistant, but the warm-season varieties are not.

Moreover, perennial grasses can be reproduced vegetatively, and they regrow rapidly after a harvest has been reaped from them. They are similar in these respects to the deciduous tree species previously discussed. Usually, more than one harvest can be reaped from them every year, but the actual number depends on the length of the growing season and the regularity and amount of rainfall and ambient temperatures during the growing season.

In those parts of the country where frosts occur every winter and, hence, where only the cool-season perennial grasses will grow, two or three harvests can usually be taken every year between the last severe frost in spring and the first one in the fall. Annual yields under these circumstances are three to five tons of oven-dry material: such yields are too low to be practical for Energy Plantations. Furthermore, because harvested

TABLE B-IV

ESTIMATED MAXIMUM YIELDS FROM VARIOUS REPRESENTATIVE DECIDUOUS TREE SPECIES IN VARIOUS LOCALITIES IN THE EASTERN AND CENTRAL TIME ZONES

OVEN-DRY TONS PER ACRE PER YEAR

Species	Planting Density (Plants per acre)	Harvest Schedule[x]	Site Location: Central Pennsylvania Musser	Site Location: Central Pennsylvania Stone	Site Location: Stoneville Mississippi	Site Location: Near Manhattan, Kansas Tuttle	Site Location: Near Manhattan, Kansas Milford	Site Location: Athens Vicinity Georgia
Hybrid Poplar								
- Clone NE 388	10,890	1-2	9.4	9.8				
- Clone NE 49	10,890	1-2		9.1				
- Clone NE 252	10,890	1-2		7.9				
Eastern Cottonwood	10,890	1-3			9.2 to 13.8[1]			
Missouri Cottonwood	10,890	1-2				11.1[2]	11.1[2]	
Sioux Cottonwood	10,890	1-2				13.7[2]	14.8[2]	
Silver Maple	10,890	1-3				7.1	7.4	
Sycamore	10,890	1-3						6 to 11.6[3]

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x Years to first harvest followed by interval in years between subsequent harvests. A total of six harvests is assumed in all cases.

1. High and low estimate - reality is probably nearer the lower estimate.

2. Determined from only one data point - the most probable characteristic yield is about twenty-five percent lower than indicated.

3. The most probable characteristic yield is about 8.8 tons per acre per year.

plant matter would have to be stored for use during the winter, cool-season grasses present many of the rather serious problems previously described for annual crops. Cool-season grasses have therefore been discarded from consideration for those parts of the country where frosts regularly occur in winter.

Cool-season grasses are not good candidates for those parts of the country which are usually frost-free the year around. As temperatures rise in summertime, their growth rate increases until the ambient temperature regularly reaches about 65° Fahrenheit. However, as it rises above this level, the rate at which cool-season grasses grow declines, and when the ambient temperature during the daytime is regularly in the upper eighties, growth ceases. Therefore, while cool-season grasses might grow well in the spring and fall in the South, they would produce very little during the summer months. They are, therefore, not satisfactory for consideration for plantations in the South.

Warm-season grasses behave quite differently. Their growth rate does not decline in the warmest months. In fact, providing there is sufficient soaking rain (two to three inches per month), their growth rate increases as the temperature rises to its peak in the summer. In many localities in the deep south, rainfall is adequate to support harvests once every three to four weeks throughout the year from late February into November. Under these circumstances, yields between eight and ten tons per year of oven-dry material are reported for managed grasslands. Warm-season grasses will probably yield about twenty percent more methane than is produced by plant matter from deciduous tree species. Thus, since the yield of plant matter from warm-season grasses in localities suited to them is comparable with that from deciduous species, warm-season grasses are likely under these circumstances to produce more methane per acre of plantation than can be produced from deciduous tree species. Certain warm-season grasses are, therefore, promising candidates for SNG plantations in those parts of the deep south where the rainfall is regular and two or more inches per month. They are particularly indicated for parts of Georgia and for the Gulf states.

Promising warm-season grasses are briefly described in Table B-V. The bermudagrasses are the most promising, although they may have to be plowed under once every six years or so to circumvent disease which may develop in the mat formed at the surface of the ground by their tillering habit. There appears to be considerable uncertainty about the seriousness of this problem. However, if they must be plowed under, their culture will have to be limited to relatively level plantation sites if soil erosion is to be avoided.

TABLE B-V

PROMISING WARM-SEASON GRASS SPECIES FOR ENERGY PLANTATIONS

Species	Localities[1]	Annual Yields[2]	Comments
Perennial Sorghums and their hybrids	Plains, South, Southwest	High	Sudangrasses, Johnson Grass and other warm-season hybrids are promising for localities with alkaline soils - they provide several harvests per year
Bermudagrasses Coastal Midland Suwanne	South and South Central States	High	Most promising of all warm-season grasses, especially for localities with acid soils - they can be harvested several times per year
Sugarcane Relatives	Lousiana and Florida	Very High	Limited suitable sites?
Bamboo Relatives	South Central United States	Untested	
Bahiagrass	Florida and southern coastal plains	High	Competes with bermudagrasses when fertilized - effect on overall yield is in dispute

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1. Regions in which species grow naturally, or have been sucessfully introduced, or have been extensively tested.

2. High means in the range of 8 to 10 dry tons per acre-year and very high, may be as much as 20 dry tons per acre-year in specially suitable sites.

VI. REFERENCE LIST

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   A. Harnfeck - Babcock and Wilcox
   W. Tanner - Foster Wheeler
   Paul Seibold - Riley Stoker Corporation
   Dean Beauregard - Detroit Stoker
   Charles C. Meyer - Weyerhauser Company.

5. Telephone interviews in June 1974 with:

   A. V. Lutes - Energex, Limited
   J. F. Lyons - Combustion Equipment Associates
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12. Deh. B. Chan and E. A. Pearson - SERL Report No. 70-3, Sanitary Engineering Research Laboratory, University of California at Berkeley, October, 1970.

13. See, for instance, Clinton C. Kemp and George C. Szego - The Energy Plantation - an invited paper presented at the AAAS Symposium, "Biochemical and Photosynthetic Aspects of Energy Conversion," in New York City, January 1975.

APPENDIX C

PREDICTION OF PLANT MATTER PRODUCTION RATES FROM DECIDUOUS TREE SPECIES IN ENERGY PLANTATIONS

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (completed)

I. INTRODUCTION

The purpose of the analysis described in this appendix is to devise a procedure for predicting harvestable plant-material yields from deciduous tree species grown in various locations and to optimize the planting and harvesting schedules for maximum average plant-material yield per acre per year. Given the average annual quantity of plant material to be produced at a plantation location, one or more deciduous species must be selected, along with the appropriate planting and harvesting schedules for each of them which will require the least land to produce the required quantity of plant material, also while minimizing the cost of the plant material produced.

At first blush, it might appear unnecessary to analyze yields of plant material which can be expected from deciduous species grown in plantations in view of the extensive effort devoted to this subject over the years by various public and private agencies concerned with pulpwood and lumber production. The problem for Energy Plantations is different, however, from that faced by pulpmakers and lumbermen. In Energy Plantations, it is necessary to maximize the average annual yield of plant material irrespective of its value as pulpwood or lumber.

The obvious approach for Energy Plantations is to consider very high planting densities (for instance, 5,000 plants per acre and more), short-growth periods before harvesting (one to eight years at most) and multiple harvests from each planting, in contrast to standard tree-farming techniques, which generally involve less than 1,000 trees per acre, twenty-years-and-longer harvest rotations and only one harvest per planting. As will appear from the analysis in this appendix, such changes in tree-farming schedules introduce drastic changes in plantation yield which justify and, indeed, require an extension of the previously used yield prediction methods.

II. PROBLEMS ASSOCIATED WITH HIGH INTENSITY PRODUCTION OF DECIDUOUS SPECIES

High-intensity production of deciduous species for their fuel value in plantations involves three aspects of technology which depart from standard practice in the forest-products industry--high planting densities, short-growth periods before harvesting and repeated, or multiple, harvests from each planting. These departures from conventional tree-farming practice introduce issues which are new. They are discussed briefly in this section.

II.A. High Planting Densities. Initial planting densities up to 10,000 plants per acre (about four square feet of land per plant), or more, are envisioned in Energy Plantations, in contrast to planting densities of 600 to 800 trees per acre in pulpwood and lumber tree farms. These high-planting densities create particular problems, of which the following two are specially important:

- survival rates - as the spacing between plants is made smaller, the plants will interfere with one another sooner and more intensively than they would at lower planting densities--the effects of shading of one plant by another, reduced space for leaf development, limited nutrient and water supply per plant and higher probability of disease spread through a plantation will tend to reduce notably the number of surviving plants after a few years--the expected increase in yield through the higher planting density will, therefore, be offset in part by a lower survival rate in the plant; and
- growth rates - close spacing between plants will also probably adversely affect their individual growth rates, and as a consequence, lower average annual yields per plant can be expected in dense plantations than in less dense ones--however, the lower growth rate per plant is offset by the greater number of plants in a dense plantation.

II.B. Harvesting After Short Growing Periods. Lumber and pulpwood trees are rarely harvested before they are fifteen years old, and very often not until they are considerably older than that. While extensive yield data have been compiled for tree species of interest to the forest products industries beginning at the age at which the trees are on the point of reaching minimum merchantable size, few data are available about their growth prior to that time. Extrapolating growth data for the period after trees have reached merchantable size backwards into the period prior to that time does not give reliable estimates of growth in their first few years after planting. Consequently, the yield tables widely used by the forest products industry are not useful for estimating plant material production rates for Energy Plantations.

Fortunately, work has been underway for nearly two decades at several places on the possibility of producing short fibre for papermaking from young deciduous tree species grown in dense plantings and harvested while they are still only a few years old. Many of these growth data have been made available for the analysis being discussed in this appendix. The sites at which these data have been compiled and the species involved are summarized in Table B-III. The estimated maximum annual yields per acre which can be expected from the combination of site and species indicated by an "O" in Table B-III are shown in Table B-IV.

II.C. Multiple Harvests per Planting. After their plant material above ground has been harvested, several deciduous tree species develop sprouts from their stumps or root systems. Among the species displaying this trait are aspen, poplar and sycamore. There are, however, at least a dozen other species which resprout vigorously in this way also. This behavior is of particular interest for Energy Plantations because it means that several harvests can be reaped from a planting, and the data available indicate that the yields of plant material from second and subsequent harvests (at least up to five or six harvests) are generally substantially higher than those from a first harvest for a given combination of species and site. To take full advantage of this multiple harvest approach in terms of the potential yield of plant material, it is necessary to develop a growth prediction procedure which relates yields from successive harvests from a planting to the land area per plant at the time of planting, the timing of the succession of harvests and certain other factors which influence plant-material yields.

III. APPROACH TO THE PROBLEM OF HIGH-DENSITY, SHORT-ROTATION PLANTATIONS

The harvestable yield of plant material in pounds per acre at year n is expressed as

$$Y_n = N_n y_n \text{ pounds per acre,} \tag{C-1}$$

where* N_n is the number of living plants per acre at year n which have survived from the initial number planted, N_o, per acre,

y_n is the average harvestable yield of plant material per plant at year n expressed as pounds per plant, and

Y_n is the yield of harvestable plant material per acre at year n expressed as pounds per acre.

The purpose for introducing explicitly the number of surviving plants in the expression for the yield is to separate, as much as possible, factors related to plant-material growth and biological phenomena accounted for by y_n, from general decay factors such as poor planting techniques, weak or dead seedlings, poor local soil quality, poor adaptation of a species to a given site, and others which are accounted for by N_n.

Both N_n and y_n depend on a number of factors such as planting density, climate, soil quality, the soil-species relationship, management of the plantation, and fertilization. In order to optimize the yield Y_n from a plantation--that is, in order to determine, for instance, the best species to be grown under given climate and soil conditions, the most appropriate planting density and harvest schedules, and the need for fertilizer--it is necessary to clarify as much as possible the nature of the dependence between N_n and y_n and the various parameters under the plantation operator's control

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* The definitions of all the symbols used in this appendix are compiled at the end of the Reference List (Section X).

and those imposed on him by nature. This clarification is the subject of the following section. Having the clarification in hand, it will then be possible to predict the species and values for the plantation parameters which will maximize the annual average harvestable yield from the plantation.

IV. ANALYSIS OF GROWTH DATA

IV.A. Plant Survival Rate at High Planting Densities in Plantations.

IV.A.1. Introduction and Summary Conclusions. The total yield of a plantation at a certain age is expressed as the product of the number of surviving plants and the yield per plant (equation C-1). Analysis of the survival data available shows that the number of surviving plants N_n at year n decreases linearly with increasing n on a semilogarithmic plot. It is found that the rate of survival for a plant species or variety well adapted to the soil and climate conditions where it is being grown increases linearly on a log-log plot with increasing land area per plant at planting time. For a given species or variety, the relation between survival and planting area is also influenced by cultural treatments (cultivation, for example) and, to a lesser extent, by fertilization.

By regression analysis of the data, the numerical constants needed for expressing the relationship between survival and planting area have been determined for several species and varieties of interest for Energy Plantations, such as cottonwoods, silver maple, sycamore and a number of hybrid poplars. These relationships can be used for predicting the survival of these species in plantations as a function of planting density (area per plant at planting time). They can also be used for calculating the yield of plant material per plant from reported yields per acre some years after the planting was made.

IV.A.2. Analysis of the Available Data. Actual numbers of surviving trees, N_n, at various ages, n, for two species at two planting densities are shown in Figure C-I. For the species and planting densities shown in the figure, the data suggest a linear dependence between log N_n and n, at least up to five years for the hybrid poplar and ten for the loblolly. This relationship is represented by an equation of the following form:

$$N_n = N_o\ 10^{-an} \text{ plants per acre at year } n \qquad \text{(C-2)}$$

where N_o is the number of plants per acre planted,

n is the number of years since planting, and

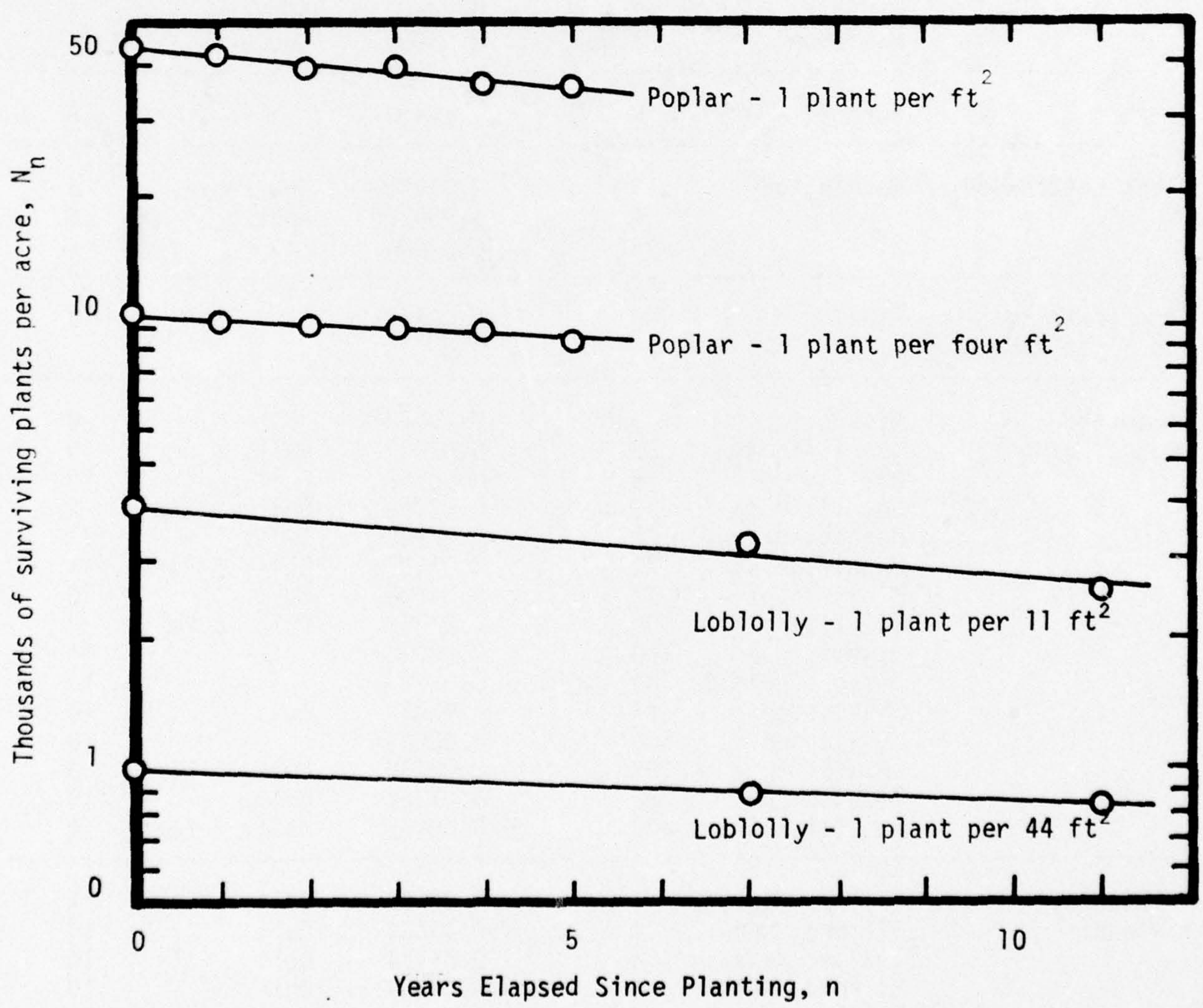
a is a decay parameter having reciprocal years as its dimension.

Values for the decay parameter a calculated using equation C-2, are shown in Table C-I for a variety of species grown in several localities. For those species shown in the table for which more than one value of the decay coefficient can be calculated, the values of the coefficient are plotted in Figures C-II through C-VII on log-log paper as a function of the land area, in square feet, per plant at planting time. This area, which is given the symbol A, is proportional to the reciprocal of N_o. For convenience, the land area per plant at planting time will be used as one of the factors for characterizing a plantation.

It will be seen from Figures C-II through C-VII that the decay coefficient a tends to be correlated as a straight line with negative slope on log-log paper when it is plotted as a function of the area per plant at planting time. The slopes appear to be approximately the same for all species. However, since this relationship is far from perfect (see particularly Figure C-VII), it is evident that other factors must also be playing a part in the relationship. Several of these factors are examined in the immediately following discussions.

FIGURE C-I

NUMBER OF SURVIVING PLANTS AS A FUNCTION OF AGE, PLANTING DENSITY AND SPECIES



Sources: Poplar - reference 1
Loblolly - reference 2

TABLE C-I

DECAY PARAMETERS CALCULATED USING EQUATION C-2

Species	Location	Planting Density ft^2/plant	Decay Parameter a	Comments[1]	Reference
Aspen	Wisconsin	0.4	0.2168	-	4
	N. Minnesota	0.76	0.07670	Suckers	3
	Manitoba	1.4	0.05465	Suckers	4
	Manitoba	1.56	0.05005	Suckers	4
Beech	Europe	0.007	1.104	-	5
Black Cottonwood	Washington[8]	1	0.05395	See foot-	6
		4	0.03528	note 8	6
		16	0.01804		6
Choctawatchee and Slash Pine	Florida	88	0.00437	-	7
Cottonwood (P. deltoides)	Mississippi[2]	5.6	0.10368	-	8
	So. Illinois	25	0.02272	Cult. & Fert.	9
	Mississippi[2]	36	0.02968	Cult.	10
	So. Illinois	50	0.02266	Cult. & Fert.	9
	Manhattan,Kan.	72	0.02288	Cult.	11
	Manhattan,Kan.	72	0.07437	Cult. & Fert.	11
	Mississippi[2]	72	0.01540	Cult.	10
	So. Illinois	100	0.01309	Cult & Fert.	9
	MIssissippi[2]	100	0.02082	-	12
	Mississippi[2]	100	0.02127	-	13
	Mississippi[2]	144	0.01452	Cult.	10
	Mississippi[2]	144	0.02246	-	13
	So. Illinois	200	0.00450	Cult. & Fert.	9
	Mississippi[2]	288	0.01222	Cult.	10
	So. Illinois	400	0.00492	Cult. & Fert.	9
Cottonwood - Missouri	Tuttle, Kans.	4	0.03529	Cult.	14
	Milford, Kans.	4	0.03024	Cult.	14
	Tuttle, Kans	8	0.01114	Cult.	14
	Milford, Kans.	8	0.04309	Cult.	14
	Tuttle, Kans.	16	0.01344	Cult.	14
	Milford, Kans.	16	0.02048	Cult.	14

TABLE C-I (continued)

Species	Location	Planting Density ft²/plant	Decay Parameter a	Comments[1]	Reference
Cottonwood - Sioux Male	Tuttle, Kans.	4	0.00439	Cult.	14
	Milford, Kans.	4	0.00664	Cult.	14
	Tuttle, Kans.	8	0.00218	Cult.	14
	Milford, Kans.	8	0.0	Cult.	14
	Tuttle, Kans.	16	0.0	Cult.	14
	Milford, Kans.	16	0.0	Cult.	14
Loblolly	S. Carolina	2.7	0.05599	-	2
	S. Carolina	5.5	0.03481	-	2
	S. Carolina	11	0.01955	-	2
	S. Carolina	22	0.01094	-	2
	S. Carolina	44	0.00745	-	2
	S. Carolina	48	0.01387	-	15
	Bainbridge,Ga.	80	0.00999	Cult. & Unfer.	16
	Bainbridge,Ga.	80	0.00861	Uncult. & Unfer.	16
	Bainbridge,Ga.	80	0.01003	Cult. & Fert.	16
	Florida	88	0.00794	-	7
Longleaf Pine	Florida	88	0.05493	-	7
Poplar Hybrids:					
Clone 49	Stone Valley,Pa.	1	0.01772	Cult.	17
	"	2	0.02288	Cult.	17
	"	3	0.01512	Cult.	17
	"	4	0.01739	Cult.	17
	"	5	0.00896	Cult.	17
Clone 252	Stone Valley,Pa.	1	0.01772	Cult.	17
	"	2	0.05674	Cult.	17
	"	3	0.02697	Cult.	17
	"	4	0.01739	Cult.	17
	"	5	0.00896	Cult.	17
Clone NE 388	Stone Valley,Pa.	1	0.03537	Cult.	17
	"	2	0.02873	Cult.	17
	"	3	0.02048	Cult.	17
	"	4	0.01739	Cult.	17
	"	5	0.01338	Cult	17
Clone NE 388	Musser Farm, Pa.	1	0.0207	Cult.	1
	"	2	0.0355	Cult.	1
	"	4	0.0127	Cult.	1
P. FNS #33-52	Saskatchewan	16	0.00536	Cult.	18
P. Tristis #1	"	16	0.01210	Cult.	18
P. Gelrica	"	16	0.01210	Cult.	18
P. Saskatchewan	"	16	0.00536	Cult.	18

TABLE C-I (continued)

Species	Location	Planting Density ft²/plant	Decay Parameter a	Comments[1]	Reference
Red Alder	Washington[7]	0.4	0.06992	Suckers	19
Sweetgum	Bainbridge,Ga.	80	0.00847	Cult. & Unfer.	16
	"	80	0.02174	Uncult. & Unfer.	16
	"	80	0.00857	Cult. & Fert.	16
Silver Maple	Tuttle, Kans	4	0.02154	Cult.	14
	"	8	0.01575	Cult.	14
	"	16	0.01024	Cult.	14
Sycamore	Georgia[6]	4	0.05781	Cult. & Fert.	21
	"	8	0.02899	Cult. & Fert.	21
	"	16	0.02583	Cult. & Fert.	21
	Athens,Ga.	16	0.3279	Footnote 3	20
	" "	16	0.0605	Footnote 4	20
	" "	16	0.0362	Footnote 5	20
	Georgia[6]	24	0.01008	Cult. & Fert.	21
	Manhattan,Kans.	72	0.04576	Cult.	11
	" "	72	0.3100	Cult. & Fert.	11
	Bainbridge,Ga.	80	0.00392	Cult. & Unfer.	16
	" "	80	0.07425	Uncult. & Unfer.	16
	" "	80	0.00429	Cult. & Fert.	16
White Ash	Massachusetts	1.8	0.04772	-	8

Footnotes:

1 - Cult. = Cultivated, Fert. = Fertilized; Uncult. = Uncultivated, Unfer. = Unfertilized.
2 - in the Mississippi River Valley in Mississippi.
3 - on upland, some planting material from one-year-old plants, others from two-year plants.
4 - on bottomland, planting material from one-year-old plants.
5 - on bottomland, planting material from two-year-old plants.
6 - on bottomland in the Piedmont.
7 - in the lower Columbia River valley.
8 - at Mount Vernon - some fertilized and some unfertilized.

FIGURE C-II

DECAY PARAMETER a AS A FUNCTION OF PLANTING AREA PER PLANT

BLACK COTTONWOOD AND SILVER MAPLE

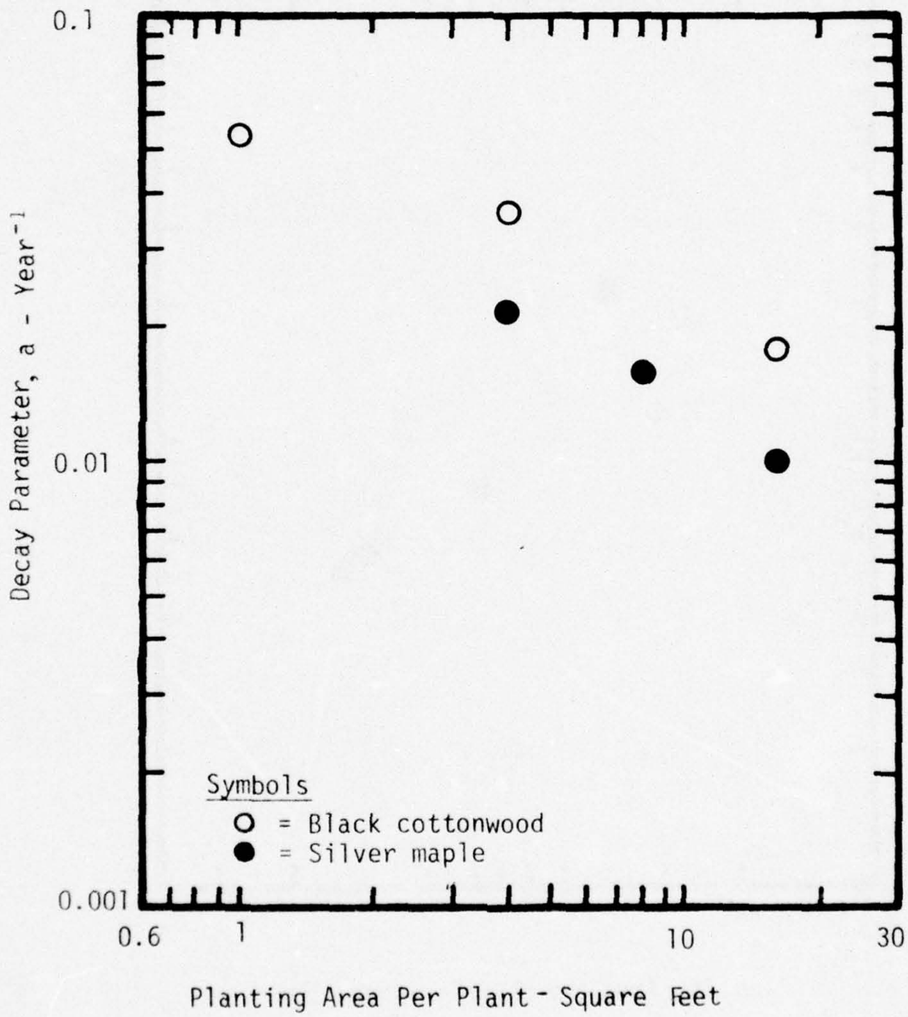


FIGURE C-III

DECAY PARAMETER a AS A FUNCTION OF PLANTING AREA PER PLANT

ASPEN

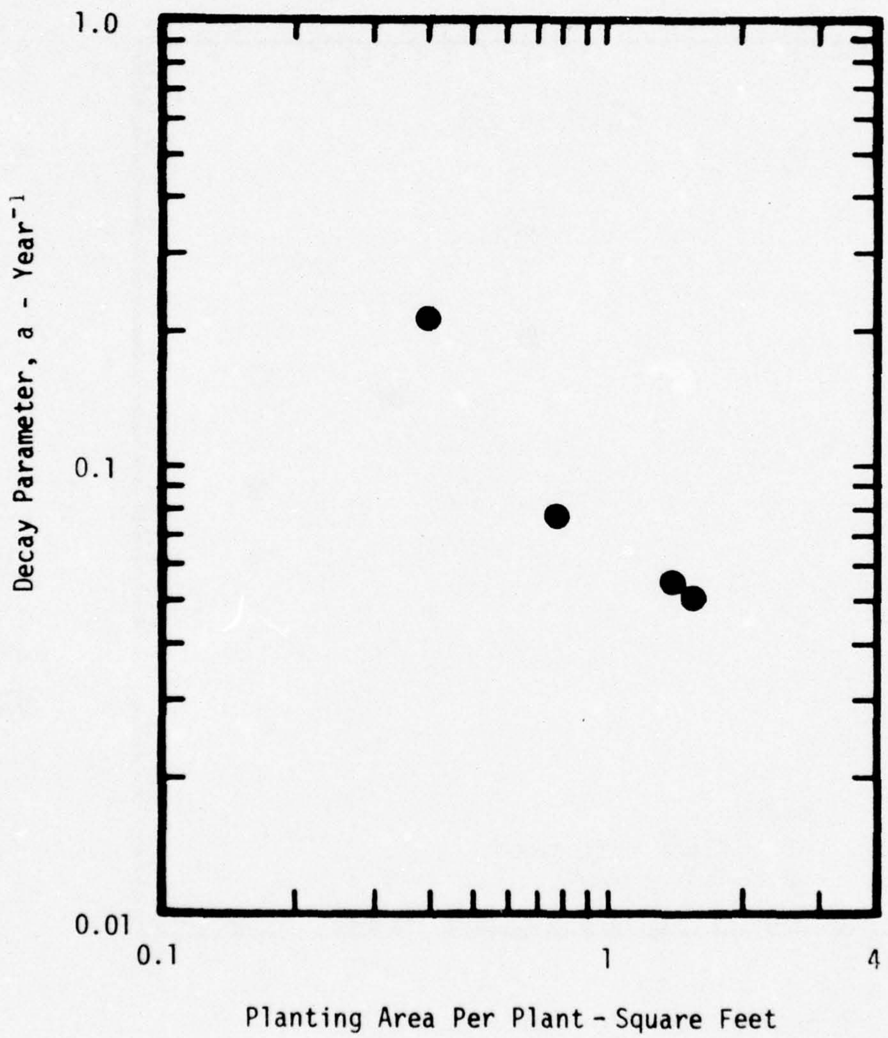


FIGURE C-IV

DECAY PARAMETER a AS A FUNCTION OF PLANTING AREA PER PLANT
HYBRID POPLAR

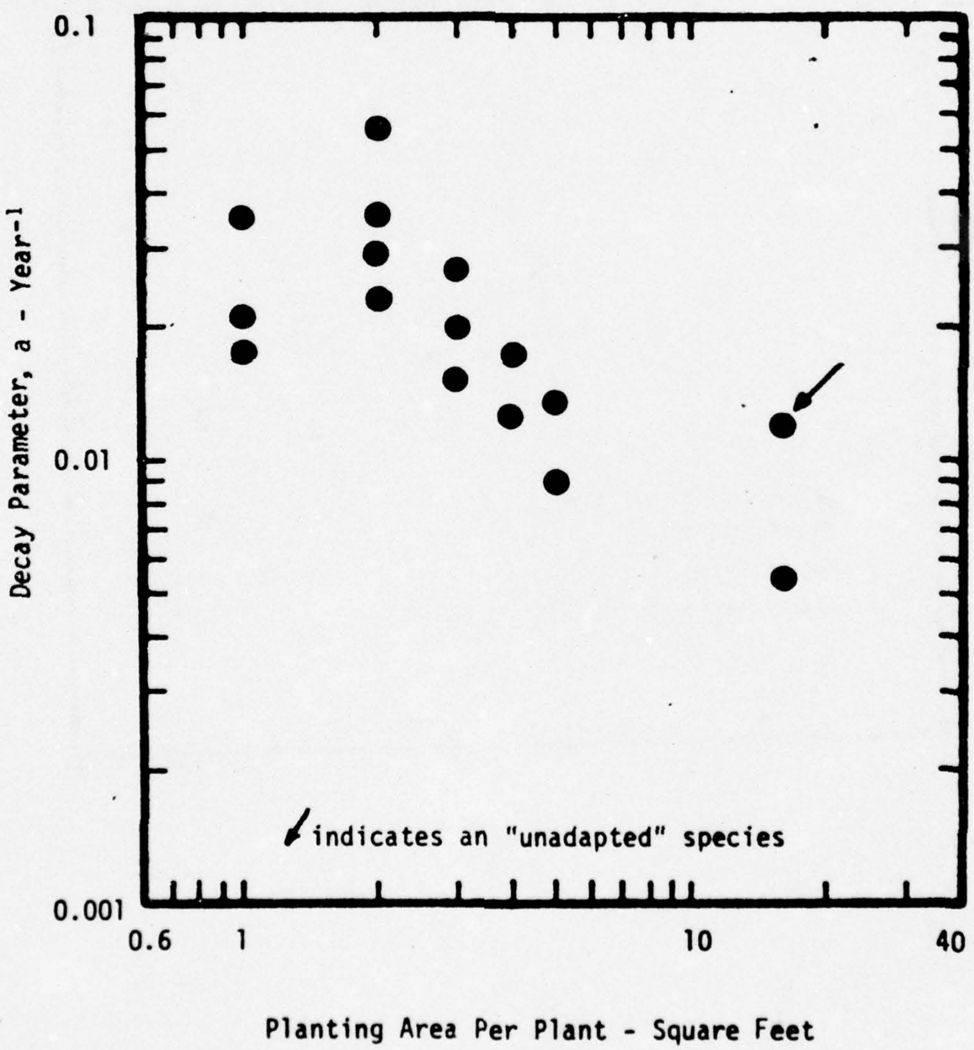


FIGURE C-V

DECAY PARAMETER a AS A FUNCTION OF PLANTING AREA PER PLANT

VARIOUS PINES

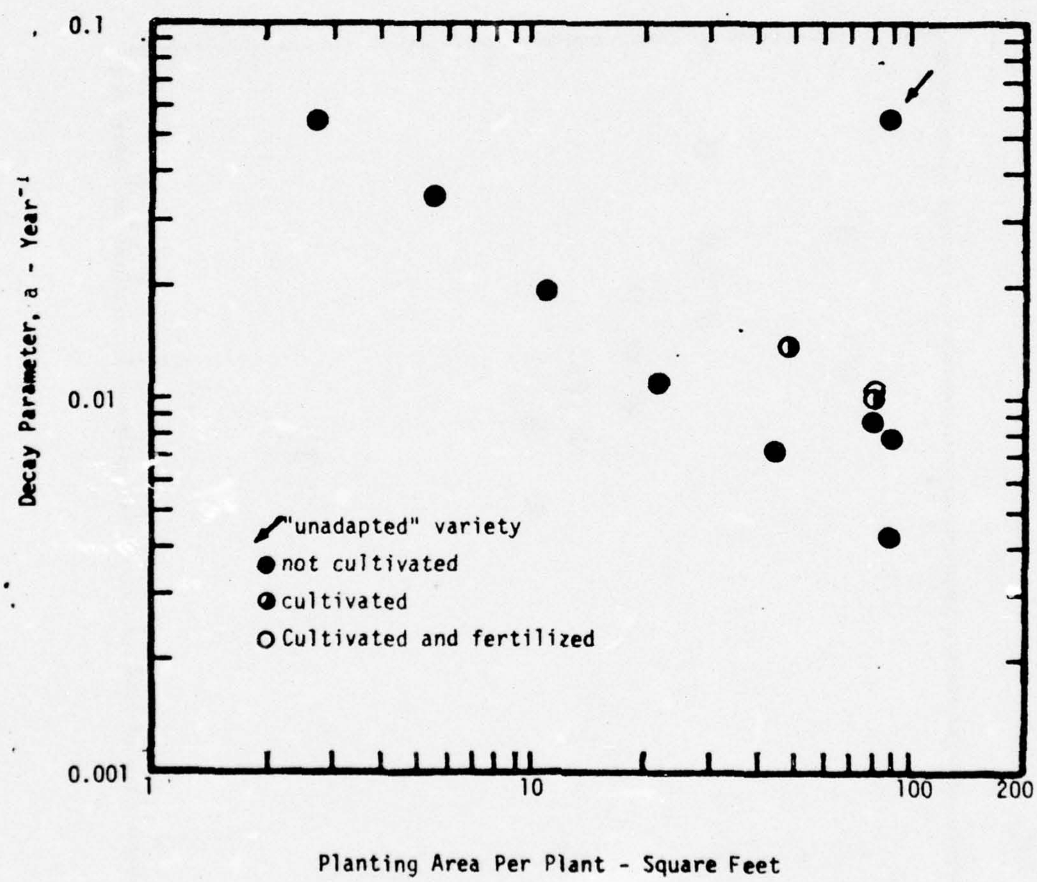


FIGURE C-VI

DECAY PARAMETER a AS A FUNCTION OF PLANTING AREA PER PLANT

SYCAMORE

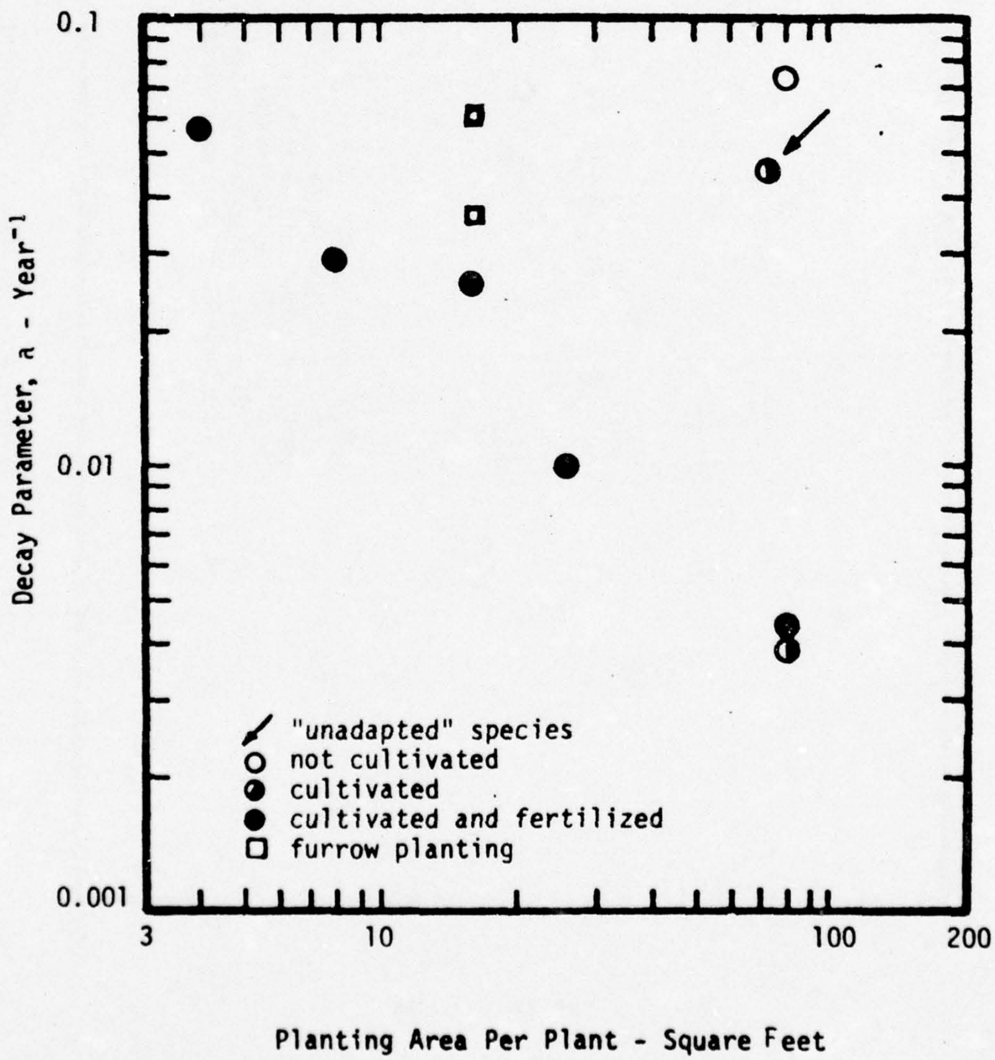
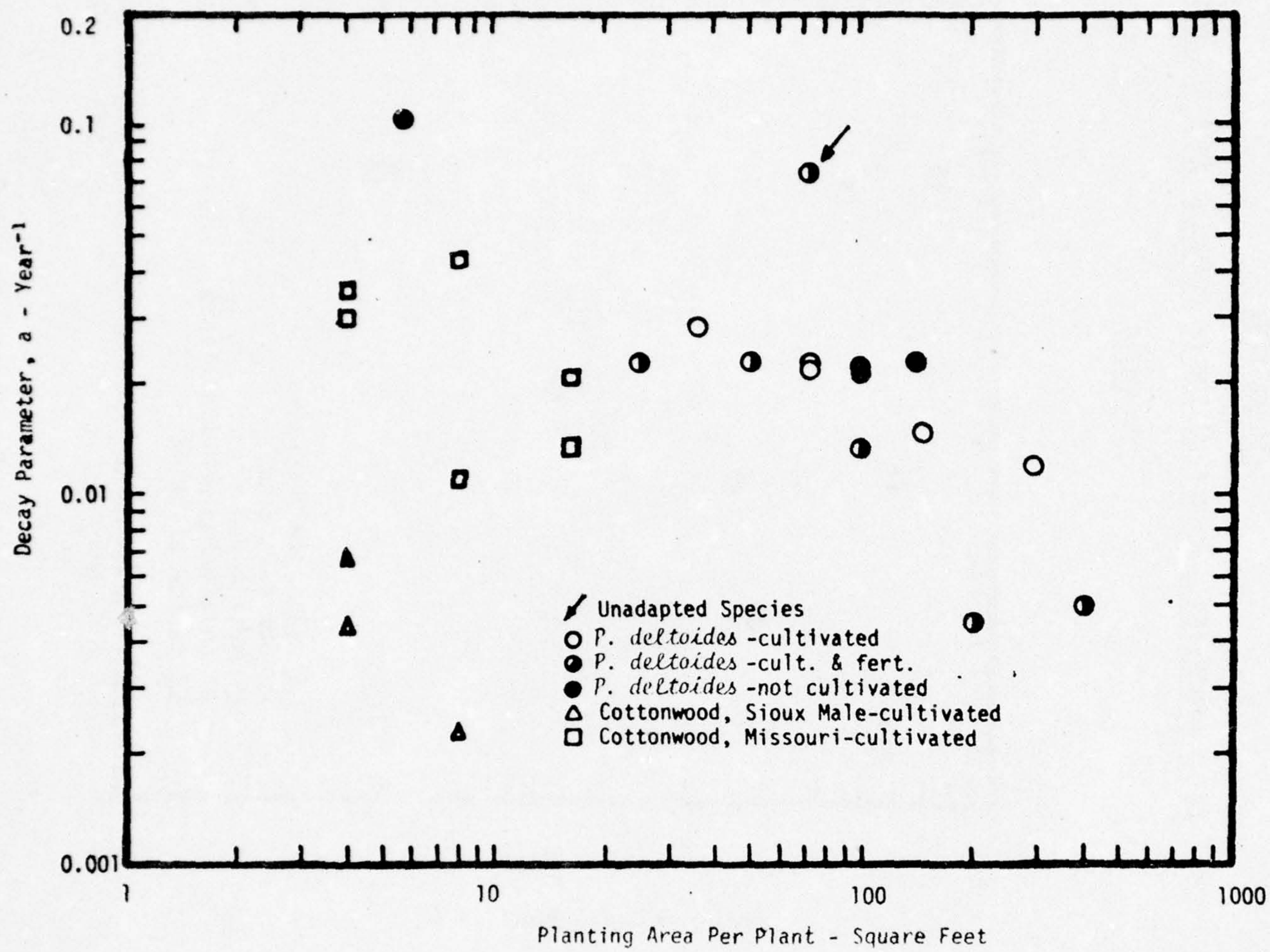


FIGURE C-VII

DECAY PARAMETER a AS A FUNCTION OF PLANTING AREA PER PLANT

COTTONWOOD



IV.A.3. Dependence of the Decay Parameter on the Planting Area per Plant. Generally speaking, the decay parameter a decreases with increasing land area per plant at planting time, which means that the rate of survival improves as the spacing between plants at planting increases. This relationship is clearly apparent in Figures C-II and C-III for black cottonwood, silver maple and aspen.

The same decreasing trend in values of a is seen from Figure C-IV for hybrid poplars, although the experimental point marked by the arrow could suggest a "flattening out" or even a reversal of the slope in the relationship between a and A. However, it is apparent from the original data in reference 18 that the two hybrid poplar varieties, P. Tristis #1 and P. Gelrica, represented by this point in the figure, are poorly adapted to the soil and climate characteristics of the test site in Saskatchewan. Because of this poor adaptation to the planting site, it is reasonable to discard the data for these two species from consideration. Such a step may appear arbitrary. It is justifiable, however, on the grounds that to establish a successful Energy Plantation in a given locality, it is necessary to select plant species or varieties of species which will grow well in--that is, they are adapted to--the particular soil, climatic and other conditions prevailing locally.

It is apparent that if consideration is limited to the well adapted species shown in Figure C-IV, the decay parameter a displays a decreasing trend as the planting area A increases.

Essentially similar comments may be made about the estimated decay parameters shown in Figure C-V for pines. The "odd" point indicated by the arrow corresponds to a longleaf pine which is known to be poorly adapted to the Florida location where the tests were conducted[7]. If consideration is centered on the other points which include data for loblolly, Choctawatchee and slash pines grown in a variety of locations in southern Georgia, South Carolina and Florida, the general decreasing trend of a as a function of the area per plant at planting time is observed. The group of seven points between the 44 and 88-square-feet-per-plant lines include data for plantings which were subject to a variety of cultural treatments. The effect of these will be discussed in a subsequent discussion. The estimates for sycamore shown in Figure C-VI appear to be rather confusing if all points are given the same importance. Under these conditions essentially no systematic trend can be discerned. The point marked with the arrow can be ruled out since it corresponds to poor adaption of species to local growing condition[11]. The spread in the estimated decay factors represented by the three data points at eighty square feet reflect the effect of various cultural practices on the growth from a particular species-site combination. These cultural practices and their effects will be discussed subsequently, but for the present, the point represented by the black dot can be set aside in an Energy Plantation discussion. The two points having the larger decay parameters at sixteen square feet per plant correspond to furrow-planted sycamore. At the time of the experiment, this technique had not been optimized. Therefore, the data on which the decay parameter estimates are based are not representative of the survival possibility of the species these days. Therefore, the two points can be safely ignored. The remaining six points shown in Figure C-VI are for sycamore-site combinations to which essentially identical cultural procedures were applied. These remaining points show the same linearity with negative slope between the decay parameter and planting area when plotted on log-log paper as is evident in Figures C-II through C-V for other species.

Estimates of decay parameters for cottonwoods are shown in Figure C-VII. The generic name "cottonwood" includes a number of well recognized varieties such as P. deltoides or eastern cottonwood, P. Missouriensis or Missouri cottonwood and male Sioux cottonwood. At first sight, the estimates in Figure C-VII do not appear to show a relationship between the decay factor and planting area evident from the other figures. However, if consideration is given to the estimates for cottonwood variety by variety and cultural treatment by treatment, a correlation similar to that in the other figures is readily apparent.

Taken together, but with allowance for species and cultural practice variation, the estimated values for the decay parameter shown in Table C-I and graphically in Figures C-II through C-VII for species well adapted to the plantation sites can evidently be correlated with the planting area per plant by an equation of the following form:

$$a = \alpha A^{\beta} \qquad \text{(C-3)}$$

where α and β are constants which are related to species, cultural treatment and perhaps some other factors. The influence of these factors will be discussed in subsequent sections.

Values of α and β obtained by regression analysis of the estimates shown in Figures C-II through C-VII are assembled in Table C-II. The regression lines corresponding to these estimates for α and β and equation C-3 are shown in Figure C-VIII. For each species or variety represented in the figure, the length of the regression line extends over the approximate range in value of planting area A for which experimental data are available. Also shown on Figure C-VIII are estimates of the decay parameter for species for which too few data are available for making a regression analysis from which to estimate an α and β in equation C-3. It is apparent that these individual points fall either within the range

IV.A.4 Dependence of Decay Parameter on Species and Varieties. Several of the estimates shown in Table C-II of the constant α in equation C-3 for particular species and cultural treatments are based on experimental data collected from more than one planting site. For instance, the estimate for hybrid poplars grown with cultivation is based on survival rates at two sites, and that for cultivated eastern cottonwood is also. An element, therefore, in the estimates of the standard deviation of several of the estimated mean values of the constant α is variation between planting sites. Variation in the performance of plant stands at each site is also an element in all the standard-deviation estimates of the values of α.

The values for α shown in Table C-II can be regarded, therefore, only as approximate estimates. A better representation of these estimates will take account also of their respective standard deviations. In recognition of this point for the purposes of this present discussion, a range in the values for α will be used, the range being defined as the estimated mean value for α plus and minus one standard deviation of the mean value. Such ranges and the estimated values for α (the lines dividing the "range" boxes) are shown in Figure C-IX for the

TABLE C-II

ESTIMATES OF THE CONSTANTS α AND β IN EQUATION C-3 FOR SEVERAL PLANT SPECIES GROWN WITH VARIOUS CULTURAL TREATMENTS

Species	Cultural Treatment	Estimates of α		Estimates of β	
		Mean Value	Standard Deviation	Mean Value	Standard Deviation
Hybrid Poplars	Cultivated	0.03121	0.00515	-0.52745	0.13373
Sioux Cottonwood	Cultivated	0.03312	0.03179	-1.30840	0.51682
Silver Maple	Cultivated	0.04621	0.00488	-0.53647	0.04889
Black Cottonwood	Chemical weed control	0.05621	0.00516	-0.39511	0.05119
Missouri Cottonwood	Cultivated	0.06304	0.05474	-0.48875	0.36434
Aspen	Not cultivated	0.07385	0.00773	-1.10372	0.18882
Pines	Some not cult., some cult., others cult. and fert.	0.08229	0.02332	-0.54365	0.07672
Eastern Cottonwood (P. deltoides)	Cultivated	0.11665	0.06698	-0.41118	0.11861
Sycamore	Cultivated and fertilized	0.20746	0.05680	-0.89112	0.08385
Eastern Cottonwood (P. deltoides)	Cultivated and fertilized	0.24214	0.18974	-0.67466	0.15288
Eastern Cottonwood (P. deltoides)	Not Cultivated	0.24650	0.05858	-0.51456	0.05625

Source: Estimates of the decay parameter a and planting area per plant A from figures C-II through C-VII.

estimated values of α for each of the seven species in Table C-II which were grown with cultivation. These species are generally recognized as being well adapted to the sites at which they were grown. Consequently, it is reasonable to assume that the cultivation--weed control--contributed with about equal effectiveness to the survival of plants at each site. Accepting this assumption and recognizing that the species were well adapted to their growth sites lead to the conclusion that there are probably significant differences in the value of α between species and, hence, also in inherent survival rates between species.

The lower horizontal scale in Figure C-IX will provide quick insight into the significance of the ranges for α shown in the figure. That scale is an estimate of the percentage of the original planting which will survive to the end of the first year, if the original planting was one plant per square foot. At that planting density, a is equal to α (see equation C-3), and the survival rate (see equation C-2) is the reciprocal of ten raised to the α power.

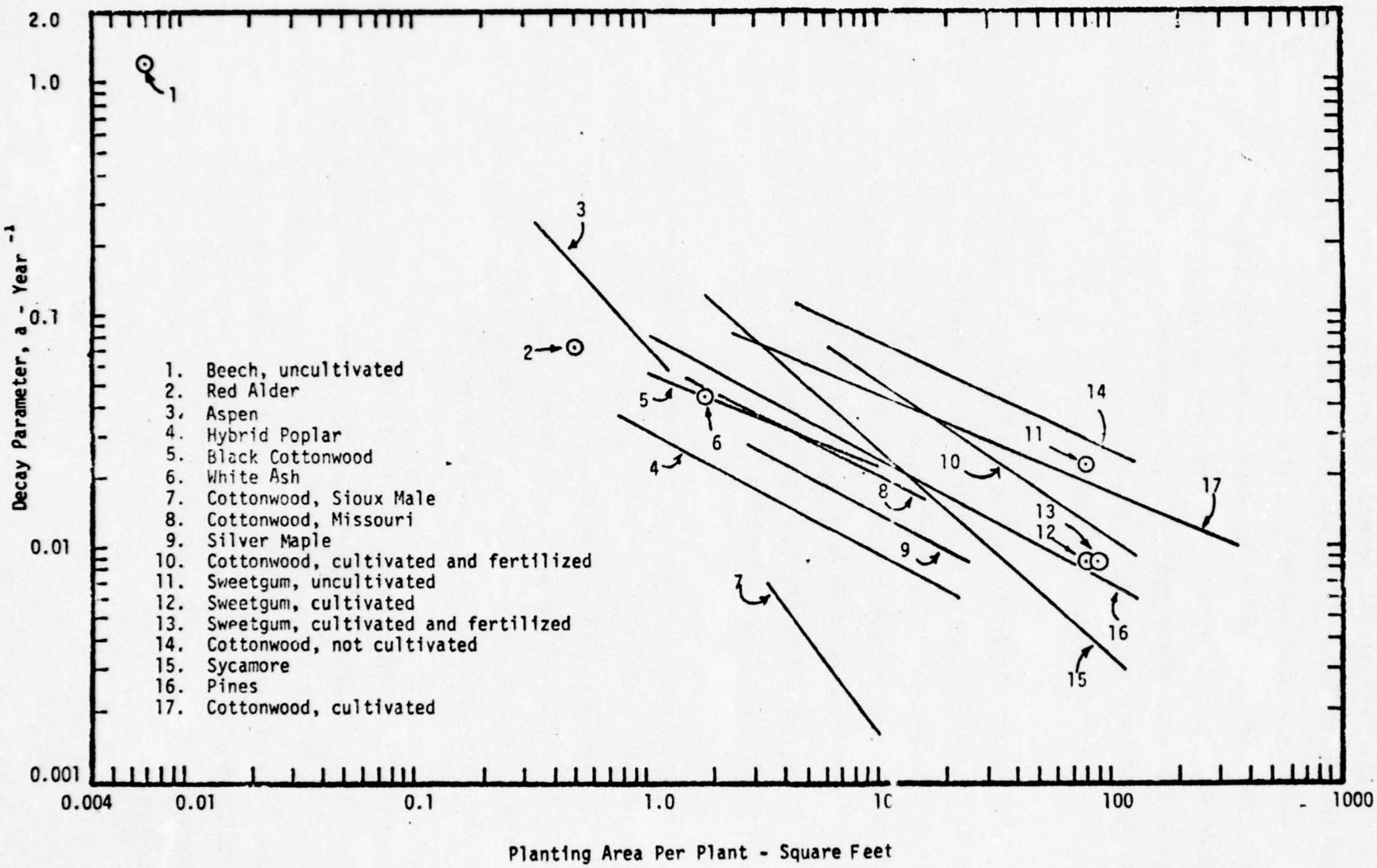
The estimates shown in Table C-IX suggest that a larger fraction of a hybrid poplar or Sioux cottonwood planting will survive to a given age than is to be expected for a pine or eastern cottonwood planting at sites to which the species are well adapted.

The constant β in equation C-3 is the slope of the regression lines shown in Figure C-VIII. It is, therefore, a measure of the rate of improvement of survival in a stand as the area per plant at planting time is increased. The higher the numerical value of β, the more rapidly survival will increase with increases in the area per plant at planting time. The value of β also affects the survival rate at a particular initial planting density. The larger its numerical value is, the greater the survival rate will be.

FIGURE C-VIII

REGRESSION LINES CALCULATED FROM EQUATION C-3

FOR DECAY PARAMETERS VERSUS PLANTING ARE FOR VARIOUS PLANT SPECIES



An analysis of the dependency of the exponent β on species is summarized in Figure C-X. This analysis is made on the same basis as that shown in Figure C-IX with respect to the constant α and its species dependency. Thus, the analysis for β is based on data for species grown with cultivation at sites to which they are well adapted. It will be seen from Figure C-X that there probably is a dependence between β and species. Sioux cottonwood, for instance, appears to have a substantially higher β than black cottonwood appears to have.

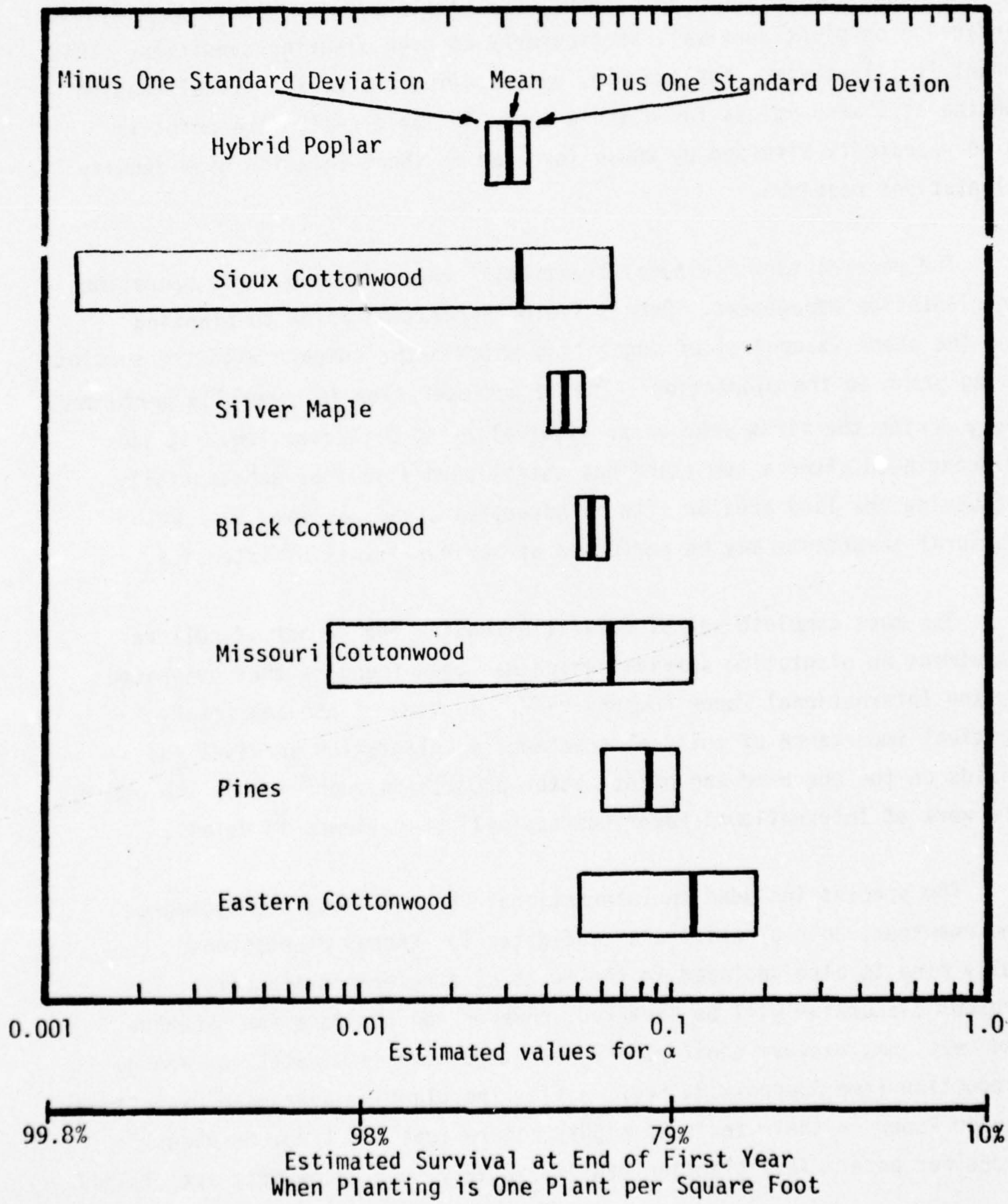
The lower horizontal scale in Figure C-X serves a similar purpose as the corresponding scale in Figure C-IX--namely, in the case of Figure C-X, to express the effect of variations in β on plant survival in a representative case. The parameters chosen for the scale are a planting area of five square feet per plant, an α equal to 0.056 (approximately the median value for alpha among the species shown in Figure C-IX) and the end of the first year after planting.

These analyses indicate that there probably are dependencies between the constants α and β in equation C-3 and species. The dependency between α and the species seems to be different from that between β and species. Note in this connection that the sequence of species is different when they are arranged in the order of increasing estimated values for α than when they are similarly arranged with respect to β.

Because of these evident dependencies, it must also be concluded that there is a dependency between the decay parameter a and species. Because so few data are available, however, it is only possible at present to assert with some confidence that such a dependency exists and to indicate its probable range--it is not possible in the absence of performance data to forecast it with any realistic reliability for particular species.

FIGURE C-IX

ESTIMATED RANGES IN THE VALUE OF α FOR SEVERAL SPECIES GROWN WITH CULTIVATION AT SITES TO WHICH THE SPECIES ARE WELL ADAPTED



IV.A.5. Influence of Cultural Treatments on Survival of Deciduous Species in Plantations. In the foregoing, several indications have arisen suggesting that the cultural management of a plantation may have a significant influence on plant survival, particularly at high planting densities. This point is illustrated, for example, by comparing the effect of cultivation on the estimated values for α and β shown in Table C-II. The point is also repeatedly stressed by those involved in short-rotation high-density plantations research.

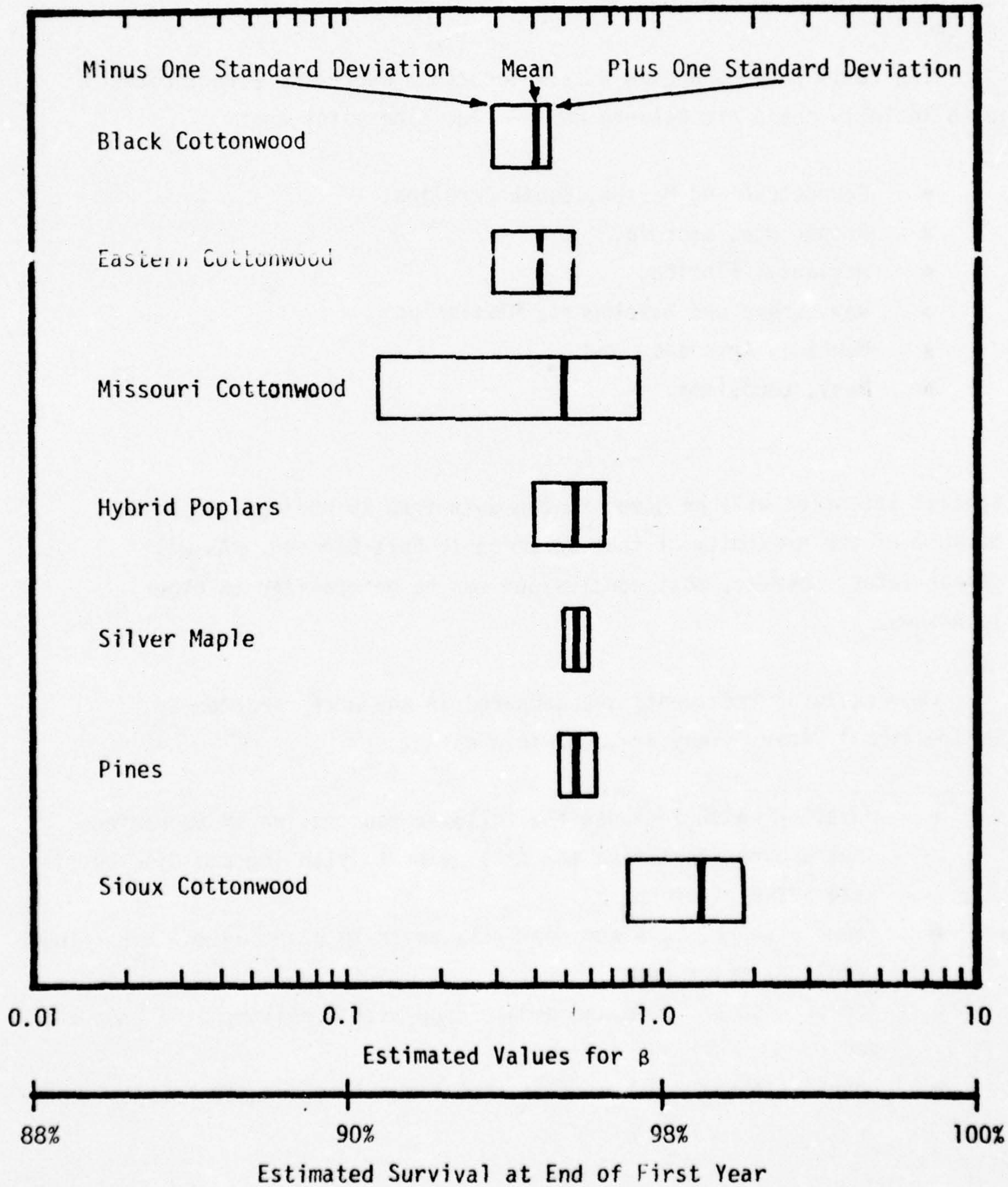
The general term "cultural treatments" refers to two field operations in plantation management. One is field preparation prior to planting and the other is control of vegetation which might compete with the species being grown in the plantation. The second operation is generally performed only during the first year or so after planting or harvesting. It is discontinued after a new stand has established itself by substantially occupying the land area or after a harvested stand has done so. Both cultural treatments may be performed at various levels of intensity.

The most complete set of data illustrating the impact of cultural treatment on plantation survival which has been found is that generated by the International Paper Company[16,22]. In view of the apparently critical importance of cultural treatment on plantation survival and yields on the one hand and plant-matter production economics on the other, the work at International Paper Company will be reviewed in detail.

The species included in International Paper's tests are sycamore and sweetgum, both of which are candidates for Energy Plantations. Loblolly pine is also included in the tests as a reference standard. The present discussion will be centered, however, on the data for sycamore and sweetgum, because conifers are not attractive candidates for energy production (see Appendix B, Section V). The planting area used by Internation Paper in their tests is eighty square feet per tree, or about 550 trees per acre. This planting density is very much below that anticipated

FIGURE C-X

ESTIMATED RANGES IN THE VALUES OF β FOR SEVERAL SPECIES GROWN WITH CULTIVATION AT SITES TO WHICH THE SPECIES ARE WELL ADAPTED



With α = 0.056 and Planting at One Plant per Five Square Feet for Energy Plantations (5,000 to 11,000 plants per acre), but the conclusions reached from International Paper's work are likely to apply also to Energy Plantation operation.

The tests were conducted at six locations where the site indices on a loblolly scale are between 80 and 110. The sites are:

- Georgetown and Marion, South Carolina,
- Bainbridge, Georgia,
- Marianna, Florida,
- Waynesboro and Hazelhurst, Mississippi,
- Manning, Arkansas, and
- Many, Louisiana.

Special attention will be given to the data from Bainbridge, Georgia, because of the proximity of that location to Fort Benning. As will appear later, however, most conclusions can be generalized to other locations.

Four cultural treatments are compared in the work reported by International Paper. They are described as:

- "disc" - which includes the following succession of operations: shear, burn, root-rake and disc prior to planting and disc cultivate after planting;
- "mow" - shear, burn and root-rake prior to planting and mow between seedlings after planting;
- "chop" - shear, burn and double chop with a rolling drum chopper; and
- "burn" - shear and burn (this treatment is the control experiment).

Survival rates for unharvested sycamore at year three for a site at Hazelhurst, Mississippi, at which four pine-site indices between eighty and 110 are represented, and for another at Bainbridge where the site index is eighty are shown in Figure C-XI. It is apparent that at the poorer sites at each location (indices eighty and ninety), the survival increases significantly as the cultural treatment becomes more intense. The data, however, for the sites having higher site indices are far less clear-cut. As a matter of fact, taking the data at face value for these more productive sites suggests that a treatment involving

- double chopping before planting and no cultivation after, or
- root-raking before planting and mowing after

adversely affects survival at more productive sites, whereas disking before and after planting seems to improve it. The operations involved in each cultural treatment shown in Figure C-XI are tabulated in the lower part of the figure.

Data comparing the effect of various site preparation methods are available on the survival of pines fifteen years after planting at sites having sandy soils in the Carolinas, Florida and Georgia[7]. The results from this study are summarized in Table C-III. Site preparation involving burning and disking or chopping apparently leads to the highest survival rates shown in the table. The action of the B.S.W. machine is similar to that achieved by choppers or discs. Thus, the results from this study are similar to those summarized in Figure C-XI. Similar results are also reported in a United States Department of Agriculture report[13] concerned with plantation production of cottonwood.

Thus, the evidence is convincing that site preparation prior to planting influences plant survival markedly. Not all conceivable preparations are equally effective, but those that are particularly so include disking in the procedure.

Cultural treatment after planting is generally concerned with control of weeds and other vegetation, which is likely to compete with the species being grown in the plantation. Competition may arise because weeds:

- shade the desired plantation species from the sunlight;
- consume moisture and nutrients from the soil which might otherwise be used by the desired species;
- by a combination of these two.

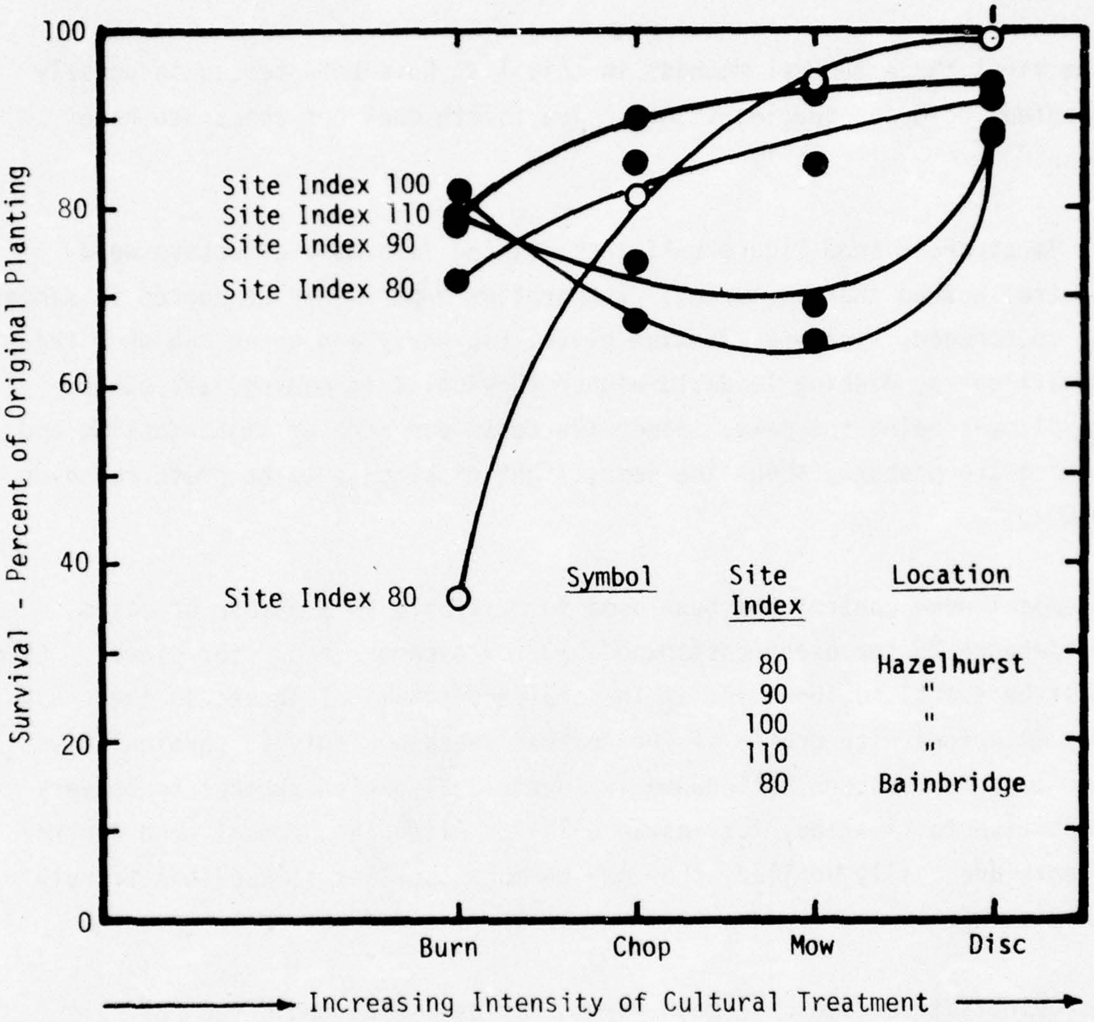
Most attention, however, seems to be given to keeping the weeds down, and thereby preventing the desired species from being shaded from the sun, rather than to preventing a cover layer in the open ground between the desired species. There is general agreement among those involved with short-rotation, high-density plantations and among more conventional foresters that control of competing vegetation, until the species being grown reaches the point where it dominates any weed growth, is essential if high survival and yield rates are to be achieved (see references 1 and 24 for hybrid poplars, 7 and 16 for pines, 13 and 23 for sycamore, reference 13 for cottonwood and 16 for sweetgum).

Control of weeds and other unwanted vegetation may be done in several ways, among which are:

- cultivation - disking, plowing or tilling,
- mowing,
- using weed killers,
- purposely planting a crop which will not shade the desired species.

FIGURE C-XI

EFFECT OF CULTURAL TREATMENT INTENSITY ON SURVIVAL RATE FOR SYCAMORE THREE YEARS AFTER PLANTING AS A FUNCTION OF SITE INDEX



	Burn	Chop	Mow	Disc
Before Planting:				
Shear	X	X	X	X
Burn	X	X	X	X
Double Chop		X		
Root Rake			X	X
Disc				X
After Planting:				
Mow			X	
Disc				X

Source: Reference 16.

The first three general methods in this list have been tested in densely planted deciduous species stands. The fourth does not appear to have been.

It is apparent from Figure C-XI that disking is a more effective weed control method than is mowing. Comparative experiments conducted in Kansas[11] on cottonwood, sycamore, Russian olive, hackberry and green ash show that in all cases, disking leads to higher survival than mowing, all other conditions being the same. Since the costs per acre of light disking and mowing are probably about the same, light disking is to be preferred over mowing.

Chemical weed control has been used successfully in a number of cases (reference 25 for black cottonwood, 23 for sycamore and 7 for pines). Care must be exercised, however, in the choice of chemical agents as their use may interfere with growth of the desired species. This is particularly the case for eastern cottonwood (*P. deltoides*), which appears to be very sensitive to Simazine, for instance[11,13]. Although chemical weed control agents are easily applied, they may be much costlier to use than to rely on disking.

No quantitative data have been formed for assessing the effect of a cover crop used for weed control on the survival rate of deciduous plant species in a plantation-like stand. The survival, as measured by visual observation, in an experiment[26] near Athens, Georgia, in which ryegrass was used as a cover crop for weed control in a sycamore plantation compared favorably with that in a parallel plantation in which mechanical weed control had been used. However, more test and cost data are needed before the relative merit of weed control by mechanical means and by cover crop can be determined.

TABLE C-III

EFFECT OF SITE PREPARATION ON SURVIVAL OF PINES IN SANDY SOILS IN THE CAROLINAS, FLORIDA AND GEORGIA FIFTEEN YEARS AFTER PLANTING

Site Preparation Procedure	Survival-Percent of original Planting
No preparation	52
Burning only	54
Burn and root-rake	61
Burn and B.S.W.[1] once	66
Burn, root-rake and disc	70
Burn and chop once	71
Burn and chop twice	71
Burn and B.S.W.[1] twice	73

1. A land-clearing machine having a sharp blade mounted like a bulldozer blade which shears protruding stems.

Source: Reference 7.

The reasons for improved survival as a result of controlling weeds and unwanted vegetation are not completely clear. One of the reasons may be that tall weeds and other tramp growth shade young seedlings from the sun, thereby decreasing their chances for survival. This is known to be the case for eastern cottonwood, which is extremely shade-intolerant during its early-growth years. Other deciduous species of potential interest for Energy Plantations are also known to be shade-intolerant. Another factor may be that weed control, particularly by disking, works plant litter into the soil near its surface, thereby contributing humus-building constituents to the soil. This same action by a disc will improve soil aeration and water retention, also. Improvement in humus content, soil aeration and water retention are known to be beneficial for plant survival and growth.

On the other hand, complete removal of ground cover may not be beneficial, because bare ground loses moisture by evaporation more rapidly than does ground which is shaded from the sun and wind. Moreover, bare ground can easily fall prey to water and wind erosion.

Thus, while the mechanisms by which cultivating the plantation site before its planting, and after, at least until the planted species dominates plant growth in the plantation are not clear, it is certain on the basis of experience generally and a number of plantation studies in particular, that

- treatment prior to planting must include cutting down and removing plant material over a few inches above ground level, but it does not appear to be necessary to remove the root structure, providing the "land" is thoroughly disked before planting, and

- treatment after planting must include sufficient disking to keep weeds and tramp growth from shading the species planted, and
- the disking program after planting must be continued until the desired species effectively shade out growth of weeds and other unwanted plants.

IV.A.6. Influence of Fertilization on Survival of Deciduous Species. It is generally agreed that deciduous trees respond to fertilization. This is particularly true for short-rotation plantations (see references 23 and 27, for instance). Fertilization, however, has been reported to have detrimental effect on the fraction of plants originally put in which survive for some years after planting time, all other conditions being the same. For instance, in the series of experiments reported by International Paper Company[16,22], it was observed that at most sites fertilization resulted in an average six percent decrease in survival rates for sycamore compared with survival in unfertilized sites. The decrease in survival rate for fertilized sites was only about three percent on the average for sweetgum when compared with the survival in unfertilized sites.

In another set of experiments[11], it was shown that granular (lawn-type) fertilizer applied shortly after planting had a strong adverse effect on survival of sycamore and eastern cottonwood. On the other hand, pellet fertilizer (22-9-2 Forest Starter Tablet) had no effect on survival of the same species. Reference to Table C-II, where values for the constants α and β in the expression for the decay parameter as a function of A are estimated, suggests that fertilization has a detrimental effect on survival, at least for eastern cottonwood. On the basis of the values for α and β given in that table for eastern cottonwood, the following survival rates at the end of the first year after planting are estimated for two planting densities:

	Survival Rates at End of First Year	
	5 ft^2/plant	8 ft^2/plant
No cultivation or fertilization	78%	82%
Fertilization and cultivation	83%	87%
Cultivation and no fertilization	87%	89%

Assuming the validity of these estimates, survival appears to be highest with cultivation without fertilization and lowest with neither cultivation nor fertilization. Reference to Table C-I shows that similar conclusions appear to apply to loblolly, sweetgum and sycamore. However, the overall effect of fertilization cannot be as simple and straightforward as these conclusions suggest.

In a number of instances where fertilizer has been used on short-rotation plantings of deciduous species, the growth and harvestable yields per acre have been larger than from parallel plantings where fertilizers were not used. These results suggest that the increased yields from plants which survived to harvest must have outweighed the yield lost by a poorer survival rate in the stand as a whole. Moreover, if plant material is to be produced intensively in a plantation, plant nutrients and other fertilizing factors must be returned to the ground if the yield from the plantation is to be maintained at a high level.

The effect of fertilization must, therefore, be complex. Because fertilizer (from ash or from spent sludge recycled from plant matter used for solid fuel or for SNG, respectively) most certainly will be used in an operating Energy Plantation, values of α and β, or the decay parameter a in the absence of α and β, estimated from fertilized stands will be used, when such are available, for estimating survival rates of plants grown under plantation conditions. In the absence of values from fertilized stands for α and β, or for the decay parameter, values for unfertilized stands will be used, knowing that whatever error may be introduced thereby is an overstatement by a few percent of the probable plant survival rate.

IV.A.7. Influence of Other Factors on Survival. There are other factors in addition to planting density, species and its adaptation to the planting site, cultivation and fertilization which have a bearing on plant survival. One of these is the soil moisture level at planting time and for a period thereafter, and another is the quality and condition of the clones to be planted.

Soil moisture, or more particularly a low level of soil moisture at planting time and for a few weeks thereafter can have a catastrophic effect on survival. There are no data which indicate what the minimum soil moisture level must be to avoid loss of survival of recently planted deciduous-species clones. One observer has, however, indicated that the soil moisture level must be high enough so that it is not the factor limiting the evapotranspiration rate from plants[28].

Clone quality and condition is rather obviously a factor having considerable bearing on the survival rate in a planting. The size of good-quality clones depends on the species. For good survival in a cottonwood or sycamore planting, clones about twenty inches long and between half and one inch in diameter are recommended[13]. For hybrid poplars, clones four to five inches long and half an inch in diameter can be successfully used, although clones about eight or ten inches long are preferred[1].

For best survival results, clones for most species are planted vertically in the ground with an inch or two remaining exposed above the ground surface. However, high survival is reported for sycamore plantings if clones about twenty inches long are buried horizontally an inch or two below the surface of the ground--"furrow planting" is the name given to this planting procedure[14].

Clones require a dormant period prior to being planted. For this reason, they are generally collected in the late fall or early winter and are stored in the dark in a moist, but not soaked, condition for three or four months at between about forty and fifty degrees Fahrenheit. Failure to follow this maturing procedure may lead to poor clone vitality and survival. Clones are generally planted in the spring while the ground is still moist near the surface.

Clones for reestablishment of stands in an Energy Plantation should be produced on the plantation itself to assure thorough adaptation of plantings to the local climate, soil and other conditions. The length and diameter requirements for clones of the species involved must therefore be taken into consideration when planning the operation of the plantation.

IV.A.8. Plant and Stump Survival Under Multiple Harvesting Conditions. One of the features of the Energy Plantation concept is that five or six, or more, harvests will be taken from each planting, thereby reducing the overall cost of planting and minimizing the danger of soil erosion by wind or rain. One of the reasons, among others (see Appendix B, Section V), that certain deciduous tree species are eminently suitable for plantation culture is their trait of resprouting vigorously and repeatedly from their stumps after harvesting.

Equation C-1 for the harvestable yield from a planting, as it is written on page C-7, assumes that the number of living plants N_n at the time of the first harvest in the n-th year is known. The main thrust of the preceding discussion of plant survival has been to devise and describe means for estimating N_n. But after the first harvest, there will be N_{n_1} * stumps remaining in the ground, most of which will resprout and provide the next harvest. The question now arises about how many stumps will survive to the second, and each of the subsequent harvests. This question is the subject of this section.

A study for sycamore[21] and another for silver maple[14] indicate that the number of surviving stumps continues to decline after the first harvest at a rate predictable from the same value for a in equation C-2 as is appropriate for estimating survival to the first harvest, if the age n years of the stand is measured from the time the stand was originally planted.

On the other hand, the yields per acre from second and subsequent harvests up to a total of five or six harvests per planting--no data on yield for more than six harvests are known to exist--are generally significantly higher than from the first for all deciduous species for which data are available. This higher yield from second and subsequent harvests than from the first can be explained by the observed fact that on the first and subsequent regrowths from the stump, several stems sprout from each stump having a total weight at harvest greater than the weight at harvest of the single stem which grew from the stump before the first harvest. But a study on sycamore[29] shows that the weights from the second and subsequent harvests from a stand are essentially identical--

---

*The subscript on N_n indicates which harvest in the sequence of harvests from a planting is being considered. The symbolic designation of the plants surviving to the second harvest is N_{n_2}, the third is N_{n_3}, and so forth.

the variation between harvests being about five percent. If it is assumed that the number of living stumps continues to decline from harvest to harvest, the implication in the light of the findings in reference 29 is either that a larger number of stems having a greater total harvestable weight sprout from each living stump after each harvest than from the immediately prior harvest, or that those stems which sprout must have more total harvestable plant material in them than did the stems from the previous harvest. Either of these possibilities, or a combination of them, would have to occur if harvestable weight is to remain essentially constant through a succession of harvests from the same planting while the number of living stumps continues to decline. there is no evidence available to support either assumption.

The rate of survival of stumps after each of a series of harvests is, therefore, uncertain in the light of the conflicting results reported in references 14, 19 and 21. It has been decided for evaluation purposes to rely on the evidence that the harvestable yield per acre tends to remain constant from the second through at least the fifth harvest, and thereby to bypass the uncertainty about stump survival during the period while these harvests are reaped.

IV.A.9. Conclusions. The analysis of the data bearing on the survival of deciduous woody species leads to the following conclusions:

1. The number of surviving plants at year n is given by

$$N_n = N_0 \, 10^{-an} \qquad \text{(C-2)}$$

where N_n = 43,560/A = number of plants per acre at planting time,
A = area per plant at planting time, square feet per plant,
n = years elapsed since planting time, and
a = decay parameter.

2. For a given species which is well adapted to a particular plantation site, the decay parameter is a function of the area per plant at planting time:

$$a = \alpha A^{\beta} \tag{C-3}$$

where α and β are constants. Because β is always negative in equation C-3, the fraction of the plants which survive always increases as the spacing between plants is increased. In fact, equation C-3 is a mathematical statement of the concept of thinning to improve yields of forests. Equation C-3 is valid over the range of planting densities from one plant per square foot to one per twenty square feet for all deciduous species for which data are available and up to one per several hundred square feet for a few species. Thus, the equation is valid over a far wider range of planting densities than will be of interest for Energy Plantations. That range is from four to about twelve square feet per plant.

3. The values of the constants α and β in equation C-3 are specific to deciduous tree species and to varieties within a species. Estimated values of the constants α and β are listed in Table C-II for the species for which enough data are available for meaningful regression analysis.

4. For a given species or variety, the values of the constants α and β depend on the cultural treatment applied to the plantation. In particular, weed control during early growth improves plant survival very significantly and is therefore a necessary operation for worthwhile plantation performance.

5. Application of fertilizer at planting time may have an adverse effect on the plant survival rate. However, it will be assumed that, provided the right type of fertilizer and application schedule are used, any adverse effect on plant survival rate is more than offset by increased yield from the surviving plants. That assumption is well substantiated by data.

6. Thus, equations C-2 and C-3 can be used to determine the survival rates of a given species or variety grown with specified cultural treatments at a wide range of planting densities. When yield data for a species are given without survival data, equations C-2 and C-3 can be used to reduce the gross yield data per acre to the yield per plant required for equation C-1. Also, in view of the similarity of the a-versus-A relationship (see Figure C-VIII) for a substantial number of deciduous species, it is suggested that when values of α and β are not available for a particular species, values of α and β for a species having similar growing habits be used to estimate the survival rate of the species for which survival data are not available.

7. Adequate moisture and good planting stock are a prerequisite for good plant survival and the establishment of a plantation. These factors may be controlled by choosing the time of planting and selecting the planting material carefully.

8. It is reasonable to assume that the number of living stumps remains essentially constant for at least five harvests subsequent to the first from a planting.

IV.B. Yields From Deciduous Species in Plantations.

IV.B.1. Introduction and Summary Conclusions. The total yield of a plantation at a certain age is expressed as the product of the number of surviving plants and the yield per plant (equation C-1). Analysis of the data available on the harvestable yield per plant shows that the yields can be expressed in terms of two constants--K_1, a growth parameter and K_2, a limiting factor--or in terms of one of these constants and a combination of the two, such as $K_1/2K_2$. Correlations have been established between the constants K_1, K_2 and $K_1/2K_2$ and the planting area per plant A, which are valid in the range of planting densities of interest for Energy Plantations. The influence of several factors, such as species, cultivation and fertilization on the constants has also been elucidated for a number of cases.

Being able to represent widely different growth data in a systematic way by a small number of characteristic constants, as well as being able to generate correlations between the characteristic constants and parameters of importance in an Energy Plantation, such as the planting density, provides an important tool for use in the design of Energy Plantations.

An approximate method for extrapolating yields from one location to another on the basis of climatological differences between the sites has also been derived.

IV.B.2. Method. The growth rate per plant per year g at year n is assumed to be

$$g = K_1 n e^{-K_2 n^2} \tag{C-4}$$

where g is the growth rate per plant per year at year n expressed as pounds (oven-dry basis) per plant per year;

n is the age of the plant material;

K_1 is a growth parameter having the dimensions pounds (oven-dry basis) per year squared; and

K_2 is a growth-limiting factor having the dimensions per year squared.

The curve represented by equation C-4 is bell-shaped when plotted against the age n of the plant material. The maximum value of the growth rate g is given by

$$g_{max} = K_1 \ (2eK_2)^{-1/2} \tag{C-5}$$

at the age

$$n_{max} = (2K_2)^{-1/2} \tag{C-6}$$

In the early years of plant-material growth, when $K_2 n^2$ is small enough to make $e^{-K_2 n^2}$ about equal to one, g is about equal to $K_1 n$ and K_1 is the slope of the growth curve when n is small. The constant K_1 is in the nature of an acceleration, whereas K_2 is a rate limiting factor.

The yield per plant y_n cumulated at year n, is given by

$$y_n = \int_0^n g(x)\, dx \qquad \text{(C-7)}$$

$$= \left(\frac{K_1}{2K_2}\right) \cdot \left[1 - e^{-K_2 n^2}\right] \text{oven-dry pounds per plant} \qquad \text{(C-8)}$$

When n is large in comparison with $K_2^{-1/2}$, y_n tends towards the asymptotic value $(K_1/2K_2)$.

Experimental yield data are generally reported as accumulated tons per acre, on an oven-dry basis or on some other one such as green weight as harvested. For consistency and to avoid error and confusion, only oven-dry weights will be used for the weight yield of plant material per plant.

It should be noted that equations having mathematical forms similar to thosein equations C-4 and C-8 have been used by others to describe the height and wood volume as a function of age in forestry yield studies[5].

IV.B.3. Computer Solutions for K_1 and K_2. In the computer program, the following notational substitutions are made:

k_1 (computer notation) = K_2 (equation notation)
k_2 (computer notation) = $K_1/2K_2$ (equation notation)

and equation C-8 in computer notation becomes

$$y_n = k_2 \left(1 - e^{-k_1 n^2}\right) \qquad \text{(C-9)}$$

The constants k_1 and k_2 are determined from two experimental points, (y_1, n_1) and (y_2, n_2), by solving

$$\left(\frac{n_2}{n_1}\right)^2 \ln\left(1 - y_1/k_2\right) = \ln\left(1 - y_2/k_2\right) \qquad \text{(C-10)}$$

for k_2 first.

Equation C-10 only has a solution if

$$\left(\frac{n_2}{n_1}\right)^2 > \frac{y_2}{y_1} \qquad \text{(C-11)}$$

Then, solve for k_1, through

$$k_1 = -\left(\frac{1}{n_1{}^2}\right) \ln\left(1 - \frac{y_1}{K_2}\right) \qquad \text{(C-12)}$$

As will appear later, in a number of cases, condition C-11 is not satisfied, that is,equation C-10 appears not to have a real solution. This situation occurs when using yield data in equation C-10 from the first year or so of plant-material growth , that is when growth is essentially unhindered by the presence of nearby plants. Under these circumstances, the only real solution for K_2 in equation C-8 is zero. Mathematically, this situation corresponds to the case where K_2n^2 in equation C-8 is small enough in the periods represented by the values of n being considered that in the series expansion of $(1 - e^{-K_2n^2})$ the value of y_n is essentially equal to

$$y_n = \frac{K_1n^2}{2} \qquad \text{(C-13)}$$

During this early period of plant-material growth, the harvestable yield increases parabolically with n and is, for all practical purposes, a function of only K_1 and n. If all the growth data available are within the range of n in which equation C-13 is a good representation of the data, there is no way for estimating a value of K_2 from the data.

IV.B.4. Average or "Best Fit" Solutions for K_1 and K_2. The values obtained for K_1 and K_2 through the computer program when condition C-11 is satisfied depend on the pair of experimental points chosen for calculating k_2 in equation C-10. Because of experimental and other nonsystematic errors in the values, the estimated values for K_1 and K_2 may depend on which pair of data points are chosen for use in equation C-10, when there are sufficient data available to allow more than one choice of data pairs.

The yield data from reference 17 for hybrid poplar clone 49 have been used to calculate values for K_1, K_2 and $K_1/2K_2$ by the computer procedure summarized in equations C-9 through C-12 for each pair of data points which can be formed from the data in the reference, which meet the requirements of equation C-11. The resulting estimates of the K factors for each pair of data points are shown in Table C-IV, along with their arithmetic averages. It will be noted that there is variation in the estimates of each of the K factors.

In the lower part of Table C-IV the yields of plant matter harvested are backcalculated using each of the groups of K-factor estimates in turn for each of the years for which yield data are available (each year up to the fourth year), and the backcalculated estimates are compared with the actually measured yields. It will be seen that:

- the backcalculated yield estimates for the harvest at the end of the first year after planting are far higher than the actually measured yields; and

- the estimates based on the average values for K_1 and K_2 (the right-hand column in the table) are closer to, and in fact almost on top of the actual harvest yields in the second, third and fourth years than are any of the estimates made for years not used in estimating the K values (the fourth year in the first column of estimates, the third in the second, and the first in the third).

Results similar to those summarized in Table C-IV are obtained when the procedure used for the table is applied to other sets of actual yield data.

In the light of the findings exemplified by Table C-IV, the following method has been adopted for estimating K_1, K_2 and $K_1/2K_2$ from yield data:

- work only with harvest yields expressed in oven-dry pounds per plant - where the harvest yield data are expressed as a green weight, convert them to an estimated oven-dry weight using the conversion factors given in reference 30;
- convert harvest yields into yields per plant either from actual plant survival data at harvest time provided by the data source or on the basis of estimates calculated by the methods summarized in section IV.A.9 of this appendix;
- calculate values of K_1 and K_2, using equations C-10 and C-12, for all pairs of harvests which satisfy the requirements of equation C-11, and average the values of K_1 and K_2 so calculated--these average estimates of K_1 and K_2 are accepted as the best estimates of the K factors which can be calculated from the yield data available for a particular species-site combination.

TABLE C-IV

VALUES OF K_1, K_2, $K_1/2K_2$ ESTIMATED BY COMPUTER ON THE BASIS OF EQUATIONS C-9 THROUGH C-12 FOR YIELDS OF HYBRID POPLAR CLONE 49 PLANTED AT ONE-SQUARE-FOOT SPACING IN CENTRAL PENNSYLVANIA

Estimated Values of Parameters

Yield data pairs[1]	Years 2+3	Years 2+4	Years 3+4	Averages[2]
Parameter K_1	0.13122	0.13921	0.16711	0.14585
Parameter K_2	0.03898	0.06966	0.09885	0.06916
Parameter $K_1/2K_2$	1.68322	0.99929	0.84527	1.05439

Backcalculated Yields Using Estimated K Factors

Year of Harvest Since Planting	Yield per Plant-y_n		Yield per Plant-y_n		Yield per Plant-y_n		Yield per Plant-y_n	
	Back-calculated o.d. lbs[3]	Percent of Actual Yield	Back-calculated o.d. lbs[3]	Percent of Actual Yield	Back-calculated o.d. lbs[3]	Percent of Actual Yield	Back-calculated o.d. lbs[3]	Percent of Actual Yield
1st	0.064	241	0.067	252	0.080	298	0.070	264
2nd	0.243	100	0.243	100	0.276	114	0.255	105
3rd	0.498	100	0.465	93	0.498	100	0.489	98
4th	0.781	116	0.671	100	0.671	100	0.706	105

Source of hybrid poplar yield data - Reference 17

Footnotes: 1. no pairs involving year-one data satisfy equation C-11.

2. average for $K_1/2K_2$ is based on the averages for K_1 and K_2.

3. oven-dry (o.d) pounds per plant.

IV.B.5. Data Analyzed. The available experimental data on the weight of harvestable material per plant from deciduous species have been analyzed by the procedure described at the end of the preceding section. Harvestable material is defined as the entire structure of plant over a few inches above ground level. In other words, after harvesting, the stump which remains at the planting site will be only a few inches high.

The results of this analysis for first harvests from plantings of several species at various sites, planting densities and age at first harvest are shown in Table C-V. The column "Average Over" in the table indicates the number of combinations of pairs of plant age at harvest time available for use (that is, they meet the requirement of equation C-11) in making estimates of K parameters.

It is probable that the estimates of the K parameters for first harvests from sycamore plantings shown in the table are less reliable than those for most other species-planting density combinations shown because only one pair of plant-age-at-harvest-time data for each of five of the six sycamore plantings meets the requirements of equation C-11, and could therefore be used for estimating K parameters. The pairs of plant-age-at-harvest-time data which could not be used for estimating K values because they do not meet the requirements of equation C-11 are examples of combinations of planting density and age of the planting at first harvest during which plant growth apparently is essentially unhindered by the planting density, and hence the appropriate value for K_2 is zero. Under these circumstances, values for K_1 can be estimated approximately by equation C-13. Values for sycamore estimated on this basis are shown in Table C-VI. The agreement between the averages of the estimated values of K_1 shown in Table C-VI and those in Table C-V (when it was possible to make an estimate based on equations C-10 and C-12) is not particularly good. But the agreement is better, although still not very good, for harvests at younger planting ages than at older ones. This finding is to be expected, because the influence of crowding between plants (the K_2 parameter) would have begun to make itself felt by harvest time in the older stands, and equation C-13 would no longer be a reliable way for estimating K_1.

The results of the analysis of experimental data on the weight of harvestable material per plant for second harvests are summarized in Tables C-VII and C-VIII. The estimated K parameters shown in Table C-VII were calculated using equations C-10 through C-12 with the values of n for the age in years of the plant material harvested being measured from the time of the first harvest. Thus, if the second harvest was taken from a particular planting three years after the first, the value used for n in the equations is three. Just as has already been noted for first harvests, there are also cases for second harvests in which the planting density and years to second harvest are such that growth interference between adjacent plants is not encountered, and therefore, the requirements of equation C-11 are not satisfied. Under these circumstances, K_2 is zero, and equation C-13 must be used for estimating the value of K_1. Two such instances are shown in Table C-VIII.

The estimated values of the K parameters listed in Tables C-V through C-VIII for the deciduous species, except aspen, red alder and quaking aspen, are plotted against the planting density per plant in Figures C-XII through C-XVII.

IV.B.6. Dependence of the Growth Parameter K_1 on Factors Characterizing a Plantation. Inspection of Figures C-XII through C-XVII indicates that the value of the parameter K_1 depends on the planting area per plant, the species, the harvest and possibly other factors. These relationships are examined in this section.

TABLE C-V

ESTIMATED VALUES OF K FACTORS CALCULATED FROM EQUATIONS C-10, 11 AND 12

FOR FIRST HARVESTS FROM DECIDUOUS-SPECIES PLANTINGS

Species	Site Locality	Cultural Treatment	Planting Density Ft^2 per Plant	Average Over	Estimated Parameter Values K_1	K_2	$K_1/2K_2$	Ref.
Aspen	Wisconsin	?	7	9	0.03554	0.004274	4.15723	4
Cottonwood (*P. deltoides*)	Mississippi[1]	Cultivated	36	15	4.55818	0.008880	256.5676	10
		"	72	15	7.57836	0.011580	327.2174	10
		"	144	15	12.38859	0.011567	535.5142	10
		"	288	11	15.92505	0.003968	2006.6852	10
Hybrid Poplars:								
Clone NE 388	Musser Farm, Pa.	Cultivated	1	4	0.14541	0.036640	1.984320	1
		"	2	4	0.23216	0.026361	4.403513	1
		"	4	4	0.37130	0.026639	6.969012	1
Clone NE 388	Stone Valley, Pa.	Cultivated	1	3	0.19599	0.056180	1.744304	17
		"	2	3	0.24632	0.043333	2.842187	17
		"	3	2	0.45739	0.071975	3.177388	17
		"	4	2	0.50885	0.035445	7.177952	17
		"	5	2	0.53151	0.039492	6.729337	17
Clone 49	Stone Valley, Pa.	Cultivated	1	3	0.14585	0.069162	1.054387	17
		"	2	2	0.21068	0.051200	2.05742	17
		"	3	2	0.21695	0.048023	2.258813	17
		"	4	2	0.27994	0.040786	3.431815	17
		"	5	1	0.27118	0.046818	2.896088	17
Clone 252	Stone Valley, Pa.	Cultivated	1	3	0.14151	0.059253	1.94142	17
		"	2	2	0.26942	0.045088	2.987713	17
		"	3	2	0.35664	0.040938	4.355855	17
		"	4	2	0.43318	0.056605	3.826340	17
		"	5	2	0.50609	0.068561	3.690764	17

TABLE C-V
(continued)

ESTIMATED VALUES OF K FACTORS CALCULATED FROM EQUATIONS C-10, 11 AND 12
FOR FIRST HARVESTS FROM DECIDUOUS-SPECIES PLANTINGS

Species	Site Locality	Cultural Treatment	Planting Density Ft^2 per Plant	Average Over	Estimated Parameter Values K_1	K_2	$K_1/2K_2$	Ref.
Slash Pine	Florida[2]	Fertilized	80	35	1.35114	0.02077	32.51841	7
		Unfertilized	80	36	1.04358	0.02793	18.68442	7
Slash and Choctawhatchee Pine	Florida[3]	Fertilized	80	10	1.00412	0.00979	51.29316	7
		Unfertilized	80	36	1.61994	0.02615	30.9740	7
Sycamore	Georgia[4]	Cult. & Fert.	4	1	1.29788	0.10359	6.26456	21
		Cult. & Fert.	8	1	0.97647	0.014215	34.34645	23
		Cultivated	4	1	0.75774	0.075007	5.051104	26
	Mississippi	Fertilized	4	3	1.50158	0.016699	44.96003	31
		"	8	1	2.18585	0.020875	52.35575	31
		"	16	1	3.73794	0.043202	43.26121	31

Footnotes:

1. in the Mississippi River Valley in Mississippi.
2. in sandy soil.
3. in sand hills.
4. in bottomland in the Piedmont.

IV.B.6.a. Influence of Planting Area per Plant. It is apparent from Figure C-XIII for cottonwood, Figure C-XIV for hybrid poplars and Figure C-XV for sycamore for first harvests from a planting that the growth parameter K_1 generally increases as the planting area per plant is increased. The same general trend is also evident for second harvests as exemplified in Figure C-XII for black cottonwood, Figure C-XVI for unfertilized sycamore and Figure C-XVII for fertilized sycamore.

It is obvious that K_1 cannot increase indefinitely as the planting area per plant is increased, because if it were to, a single isolated plant in a very large area would grow at a near infinite rate. It is common knowledge that such does not occur. In fact, examination of Figure C-XIII for cottonwood suggests that the rate of increase in the value for K_1 tapers off as the planting area per plant becomes large--for instance, when it is greater than about 150 square feet. It is reasonable to assume tnat K_1 reaches an asymptotic value as the planting area is increased, in which case the data for K_1 in Figure C-XIII can be represented by

$$K_1 = \lambda_1 (1 - e^{-\lambda_2 A}) \qquad \text{(C-14)}$$

This equation follows the shape of the estimates for K_1 shown in Figure C-XIII, because if λ_1 and λ_2 are truly constants, and if the value of λ_2 is less than one, then:

- when the planting area per plant A is small, K_1 will be a linear function of A; and
- when A is large, K_1 will equal the constant λ_1.

Using the values for K_1 in Figure C-XIII at thirty-six and 288 square feet, equation C-14 becomes

$$K_1 = 17.4859 (1 - e^{-0.0083895A}) \qquad \text{(C-15)}$$

TABLE C-VI

ESTIMATED VALUES OF K_1 CALCULATED FROM EQUATION C-13
FOR FIRST HARVESTS FROM SYCAMORE GROWN IN BOTTOMLAND IN THE GEORGIA PIEDMONT

Cultural Treatment	Planting Density Ft^2 per Plant	Estimated Values of K_1 Based on Harvests at Indicated Planting Age: 1 Year	2 Years	3 Years	4 Years	Average of K_1 Values	Ref.
Cult. & Fert.	4	0.42202	0.55158	-	0.66020	0.52978	23
		0.48334[a]					23
	8	0.35630	0.94922	-	0.87338	0.65358	23
		0.43546[a]					23
	16	0.38256	0.75666	-	1.41946	0.73530	23
		0.38256[a]					23
	24	0.56658	1.01982	-	1.33322	0.84322	23
		0.45326[a]					23
Cult. & Fert.	4	-	1.06258	0.84412	-	0.95335	21
	8	-	0.76906	1.02473	-	0.89689	21
	16	-	1.35016	2.05598	-	1.70307	21
	24	-	1.67182	2.58962	-	2.13072	21
Cultivated	4	-	0.65462	0.55098	-	0.60280	26
	8	-	0.52260	2.05794	-	1.29027	26
	16	-	0.33852	0.62676	-	0.48264	26
	24	-	0.55362	1.18572	-	0.86967	26

Footnote: a - values from a second site.

TABLE C-VII

ESTIMATED VALUES OF K FACTORS CALCULATED FROM EQUATIONS C-10, 11 AND 12 FOR SECOND HARVESTS FROM DECIDUOUS-SPECIES PLANTINGS

Species	Site Locality	Footnotes	Planting Density Ft^2 per Plant	Average Over	Estimated Parameter Values K_1	K_2	$K_1/2K_2$	Reference
Black Cottonwood	Mt. Vernon, Wash.	1	1	1	0.20362	0.052515	1.938678	19
		1	4	1	1.15821	0.099774	5.804181	19
		1	16	1	2.87262	0.041842	34.327047	19
Hybrid Poplar - Clone NE-388	Musser Farm, Pa.	2	1	2	0.64320	0.419744	0.765899	1
		2	2	2	1.71124	0.368125	2.324261	1
		2	4	2	2.28317	0.276121	4.134369	1
Red Alder	Washington	3	0.4	6	0.01901	0.064731	0.146823	19
Sycamore	Georgia	4	4	1	1.12621	0.211582	2.661401	23
		4	8	1	1.95062	0.295567	3.299791	23
		4	16	1	2.04137	0.193387	5.277949	23
		4	24	1	7.15873	0.580430	6.166751	23
		5	4	1	1.95388	0.122422	7.980090	21
		5	8	1	3.05393	0.206739	7.385966	21
		5	16	1	4.99550	0.203545	12.271242	21
		5	24	1	9.89241	0.261035	18.948433	21
		6	4	3	1.49034	0.187530	3.973591	29
		6	8	2	2.44008	0.147594	8.266183	29
		6	16	2	5.85950	0.147281	19.892145	29

TABLE C-VII
(continued)

ESTIMATED VALUES OF K FACTORS CALCULATED FROM EQUATIONS C-10, 11 AND 12 FOR SECOND HARVESTS FROM DECIDUOUS-SPECIES PLANTINGS

Species	Site Locality	Footnotes	Planting Density Ft^2 per Plant	Average Over	Estimated Parameter Values K_1	K_2	$K_1/2K_2$	Reference
		7	8	1	1.87926	0.258449	3.635643	26
		7	24	1	4.76974	0.187996	12.685744	26
		8	4	1	0.83935	0.143304	2.928563	26
		8	8	1	1.55992	0.146533	5.322748	26
		8	24	1	2.82819	0.056768	24.910082	26
		9	8	1	0.30139	0.067377	2.236585	32
		9	16	1	0.65430	0.169715	1.927641	32
		10	16	1	2.49336	0.011178	111.529683	31

Footnotes:	Cultural Treatment	Stump Age at First Harvest	Other Comments
1	mixture of fert. & unfert.	2 years	-
2	cultivated	1 - 3 years	-
3	?	?	In the lower Columbia River valley
4	fertilized	1 year	In bottomland in the Piedmont
5	cult. & fert.	1 year	In bottomland in the Piedmont
6	fertilized	2 years	In upland in the Piedmont
7	unfertilized	1 year	In bottomland in the Piedmont at Skull Shoals
8	unfertilized	1 year	In bottomland in the Piedmont at Falling Creek
9	unfertilized	1 & 2 years	In bottomland in the Piedmont
10	?	2 years	Mississippi

This equation represents the two other values for K_1 in Figure C-XIII to within less than five percent error. A functional dependence between K_1 and the planting area per plant A of the form of equation C-14 is probably a good approximation.

However, in many cases--see, for instance, the data for hybrid poplar in Figure C-XIV--the range of values of A for which K_1 estimates are available is too narrow to permit determination of the constants λ_1 and λ_2 in equation C-14. These cases are those for which $\lambda_2 A$ is small enough for the exponential term in equation C-14 to have a strong influence on K_1. However, by taking the logarithm of equation C-14 and expanding the exponential as a series in $(\lambda_2 A)$, log K_1 can be expressed as:

$$\begin{aligned} \log K_1 &= \log \lambda_1 + \log (1 - e^{-\lambda_2 A}) \\ &\simeq \log \lambda_1 + \log (\lambda_2 A) + \log \left(1 - \frac{\lambda_2 A}{2}\right) + \ldots\ldots.. \\ &\simeq \log \lambda_1 + \log (\lambda_2 A) \qquad \text{(C-16)} \end{aligned}$$

Equation C-16 suggests that for low enough values of A for $\lambda_2 A$ to be small with respect to one, a linear relationship between K_1 and A exists on a log-log plot. This is indeed what the experimental data suggest in Figure C-XII and in figures C-XIV through C-XVII for first and second harvests.

In light of the finding, the dependence between K_1 and A can be represented approximately as:

$$K_1 = \mu_1 A^{\mu_2} \qquad \text{(C-17)}$$

TABLE C-VIII

ESTIMATED VALUES OF K_1 CALCULATED FROM EQUATION C-13 FOR SECOND HARVESTS FROM DECIDUOUS SPECIES

Species	Site Locality	Footnotes	Planting Density Ft^2 per Plant	Estimated Values of K_1 Based on Harvests at Indicated Years Since First Harvest				Average of K_1 Values	Ref.
				1 Year	2 Years	3 Years	4 Years		
Quaking Aspen	New Hampshire	1	1	0.05442	0.06129	0.15294	-	0.08955	33
		1	2	0.05963	0.07530	0.19405	-	0.10966	33
		1	4	0.09527	0.09884	0.25980	-	0.15131	33
Sycamore	Mississippi	2	4	-	1.28041	1.52123	1.67364	1.49176	31
		2	8	-	1.53617	1.76550	1.84885	1.71351	31
		2	16	-	1.72712	2.37203	2.28310	2.12742	31

Footnotes:

	Stump Age at First Harvest	Cultural Treatment
1	2 Years	?
2	2 Years	unfertilized

which is the equivalent of

$$\log K_1 = \log \mu_1 + \mu_2 \log A \tag{C-18}$$

for the relatively small values of A of interest for Energy Plantations. Comparing equation C-16 with equation C-18, it is apparent that

$$\log \mu_1 \simeq \log \lambda_1 + \log \lambda_2 \tag{C-19}$$

and $$\mu_2 \simeq 1 \tag{C-20}$$

The relations C-19 and C-20 will not be strictly true because higher order corrective terms, such as $\log (1 - \lambda_2 A/2)$, have been ignored in equation C-16.

The approximation represented by equation C-17 has been tested for cottonwood (data in Figure C-XIII) and for low values of A (up to about thirty square feet per plant). It is found to represent the values given by equation C-15 to within less than two percent.

Relations of the form of equation C-17, therefore, will be used to represent the K_1 versus A dependence.

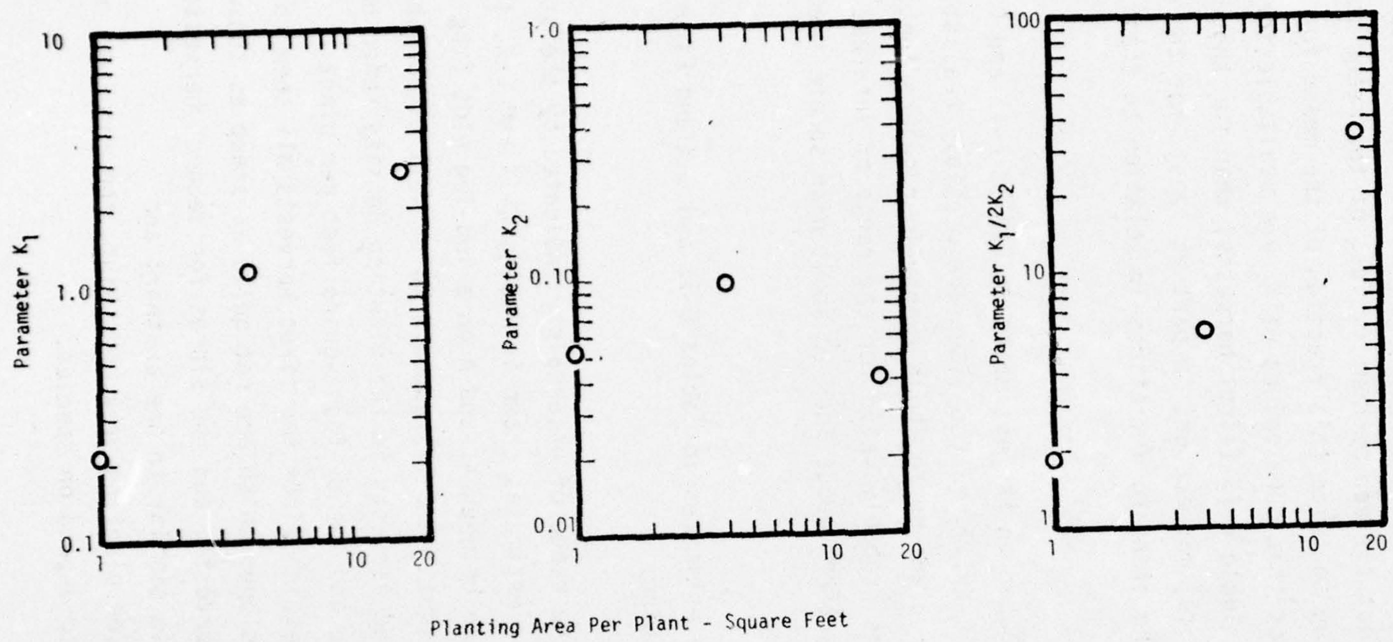
Regression analyses on the basis of equation C-17 have been made between the values of A and K_1 shown in tables C-V, C-VI and C-VII for all species except the pines, aspen and red alder. These plantings were excluded from consideration for various reasons, including, in some cases the species being of no interest for Energy Plantations, the planting density being far higher than is practical for fuel production and no record of the number of plants surviving at harvest time. The regression values for μ_1 and μ_2 and their respective standard deviations are shown in tables C-IX and C-X for first and second harvests, respectively. It will be seen that the standard deviation for the

<u>FIGURE C-XII</u>

<u>BLACK COTTONWOOD</u>

<u>ESTIMATED VALUES OF K PARAMETERS VERSUS PLANTING AREA PER PLANT</u>

<u>SECOND HARVEST ONLY</u>



Source: Table C-VII.

two μ's reflecting first harvests are smaller in relation to their respective means than is the case for second harvests. Standard deviations are about fifteen percent or less of the means for first harvests and are up to twice this fraction of the means for second harvests. The fact that more values of K_1 are available for many of the species listed in Table C-IX (first harvests) than for those in Table C-X (second harvests) may account in part at least for the difference in the value of the standard deviations in relation to their respective means.

Regression lines based on the estimates in Tables C-IX and C-X are plotted in Figure C-XVIII. These lines are probably realistic for planting areas per plant up to about twenty-four square feet, which means that they are probably valid for the range of interest for Energy Plantations (from about four to about nine square feet per plant).

Examination of the estimates in Tables C-IX and C-X and Figure C-XVIII suggests the following:

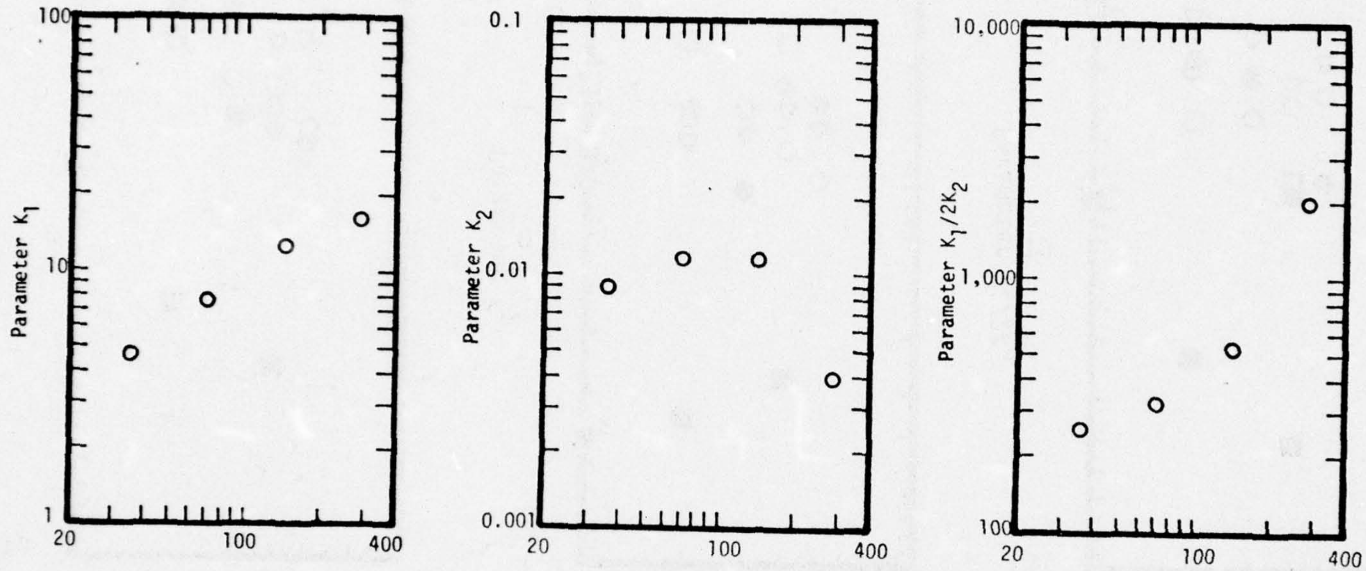
- within the range of uncertainty indicated by the standard deviation estimates shown in Tables C-IX and C-X, the linear dependence between K_1 and A on a log-log plot (the equivalent of equation C-17) appears to be well established for first and second harvests in the planting density range between about one and twenty-four square feet per plant;
- the regression lines for first harvests all seem to have similar slopes which are not quite as steep as those for second harvests, and the slopes for second harvests are also quite similar to one another; and
- for a given planting area per plant, the absolute values of K_1 seem to depend on species.

FIGURE C-XIII

COTTONWOOD (P. deltoides)

ESTIMATED VALUES OF K PARAMETERS VERSUS PLANTING AREA PER PLANT

FIRST HARVEST ONLY



Planting Area Per Plant - Square Feet

Source: Table C-V.

FIGURE C-XIV

HYBRID POPLAR - CLONES 49, 252 AND NE 388

ESTIMATED VALUES OF K PARAMETERS VERSUS PLANTING AREA PER PLANT

FIRST HARVESTS AND SECOND HARVEST FOR CLONE NE 388 AT MUSSER FARMS

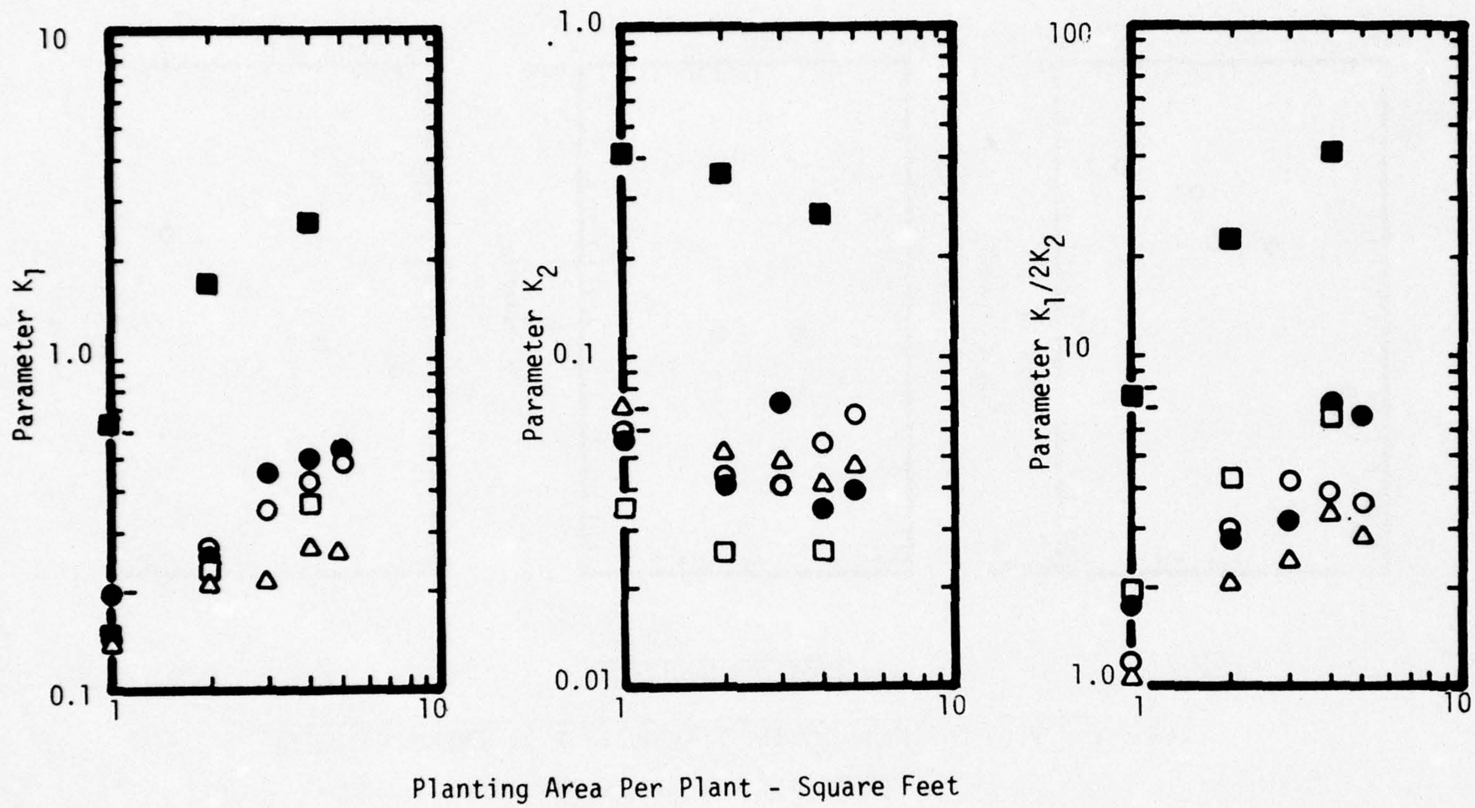


FIGURE C-XIV (continued)

HYBRID POPLAR - CLONES 49, 252 AND NE 388

ESTIMATED VALUES OF K PARAMETERS VERSUS PLANTING AREA PER PLANT

FIRST HARVESTS AND SECOND HARVEST FOR CLONE NE 388 AT MUSSER FARMS

LEGEND AND SOURCES

Hybrid Poplar	Harvest	Symbol	Source
NE 388 (Musser Farm)	First	□	Table C-V
NE 388 (Musser Farm)	Second	■	Table C-VII
NE 388 (Stone Valley)	First	●	Table C-V
49	First	△	Table C-V
252	First	○	Table C-V

FIGURE C-XV

SYCAMORE

ESTIMATED VALUES OF K PARAMETERS VERSUS PLANTING AREA PER PLANT

FIRST HARVESTS ONLY

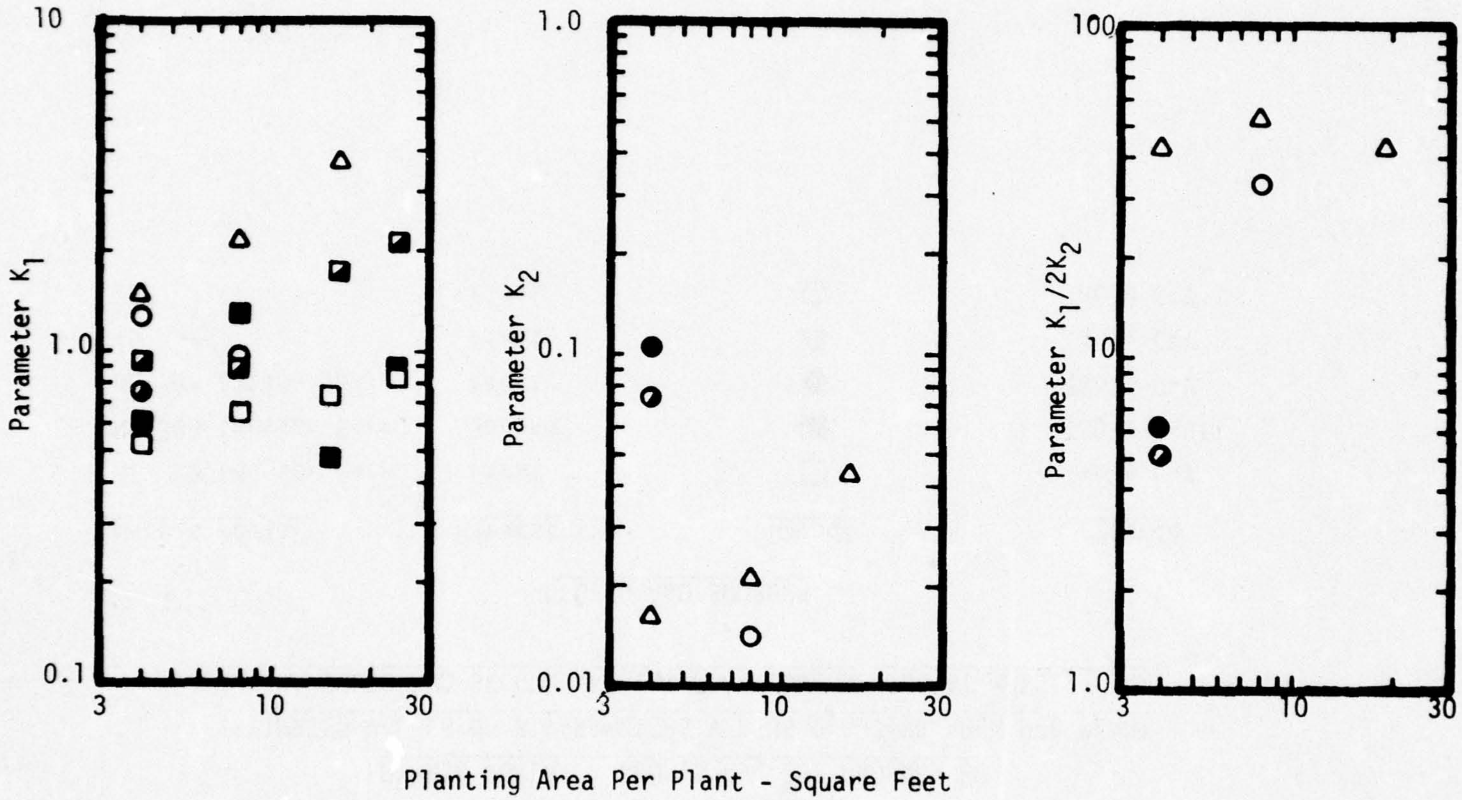


FIGURE C-XV (continued)

SYCAMORE

ESTIMATED VALUES OF K PARAMETERS VERSUS PLANTING AREA PER PLANT

FIRST HARVESTS ONLY

LEGEND AND SOURCES

Site (note 1)	Cultural Treatment	Symbol	Source
Georgia	Cult. and Fert.	●	Table C-V
Georgia	Fertilized	○	Table C-V
Georgia	Cultivated	◕	Table C-V
Mississippi	Fertilized	△	Table C-V
Georgia	Cult. and Fert.	◪	Table C-VI
Georgia	Cult. and Fert.	□	Table C-VI
Georgia	Cultivated	■	Table C-VI

Note 1: All the Georgia sites are bottomland on the Piedmont.

FIGURE C-XVI

UNFERTILIZED SYCAMORE

ESTIMATED VALUES OF K PARAMETERS VERSUS PLANTING AREA PER PLANT

SECOND HARVESTS ONLY

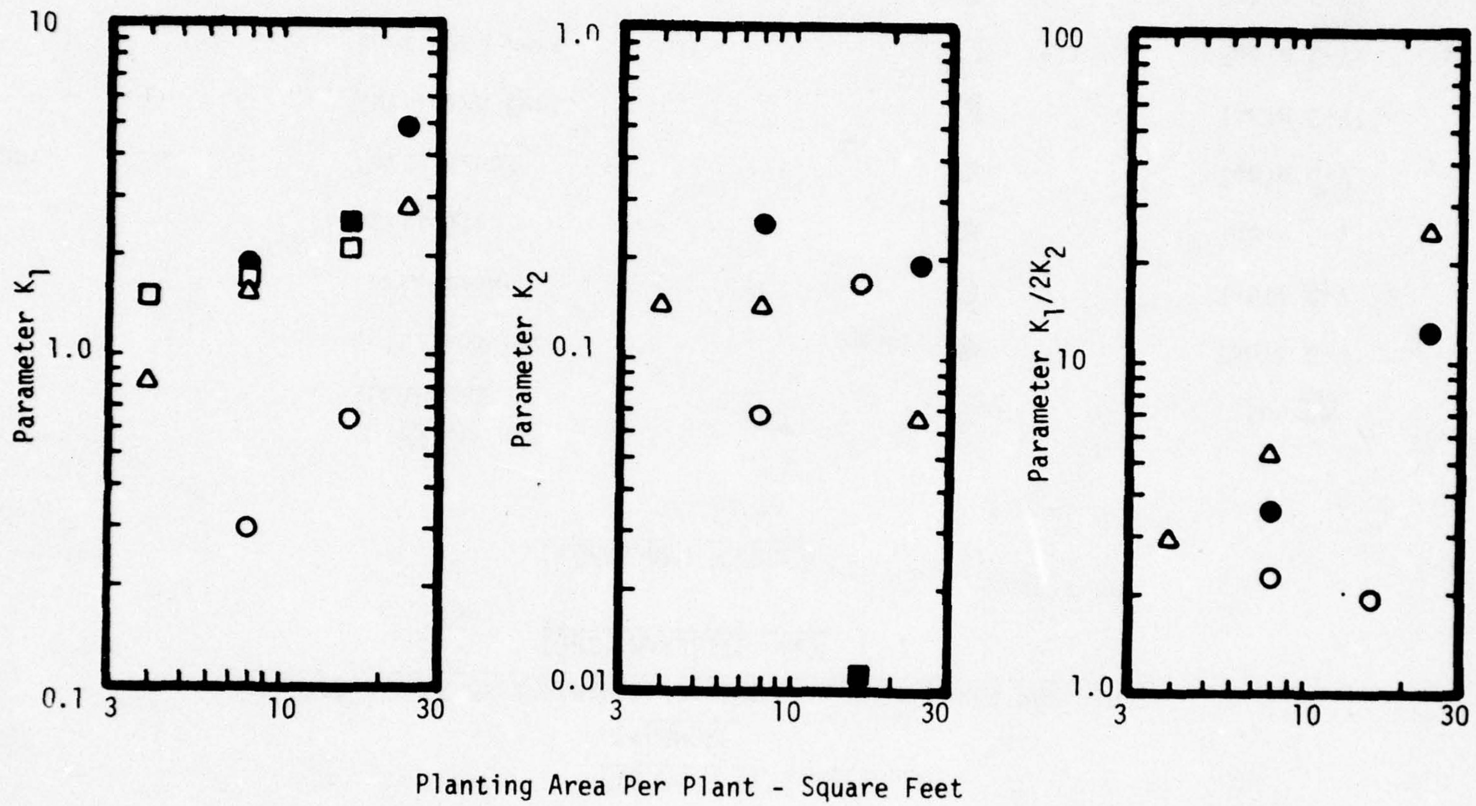


FIGURE C-XVI (continued)

UNFERTILIZED SYCAMORE

ESTIMATED VALUES OF K PARAMETERS VERSUS PLANTING AREA PER PLANT

SECOND HARVESTS ONLY

LEGEND AND SOURCES

Site (Note 1)	Symbol	Source
Skull Shoals, Ga.	●	Table C-VII
Falling Creek, Ga.	△	Table C-VII
Georgia	○	Table C-VII
Mississippi	■	Table C-VII
Mississippi	□	Table C-VIII

Note 1: All Georgia sites are bottomland in the Piedmont.

FIGURE C-XVII

FERTILIZED SYCAMORE

ESTIMATED VALUES OF K PARAMETERS VERSUS PLANTING AREA PER PLANT

SECOND HARVESTS ONLY

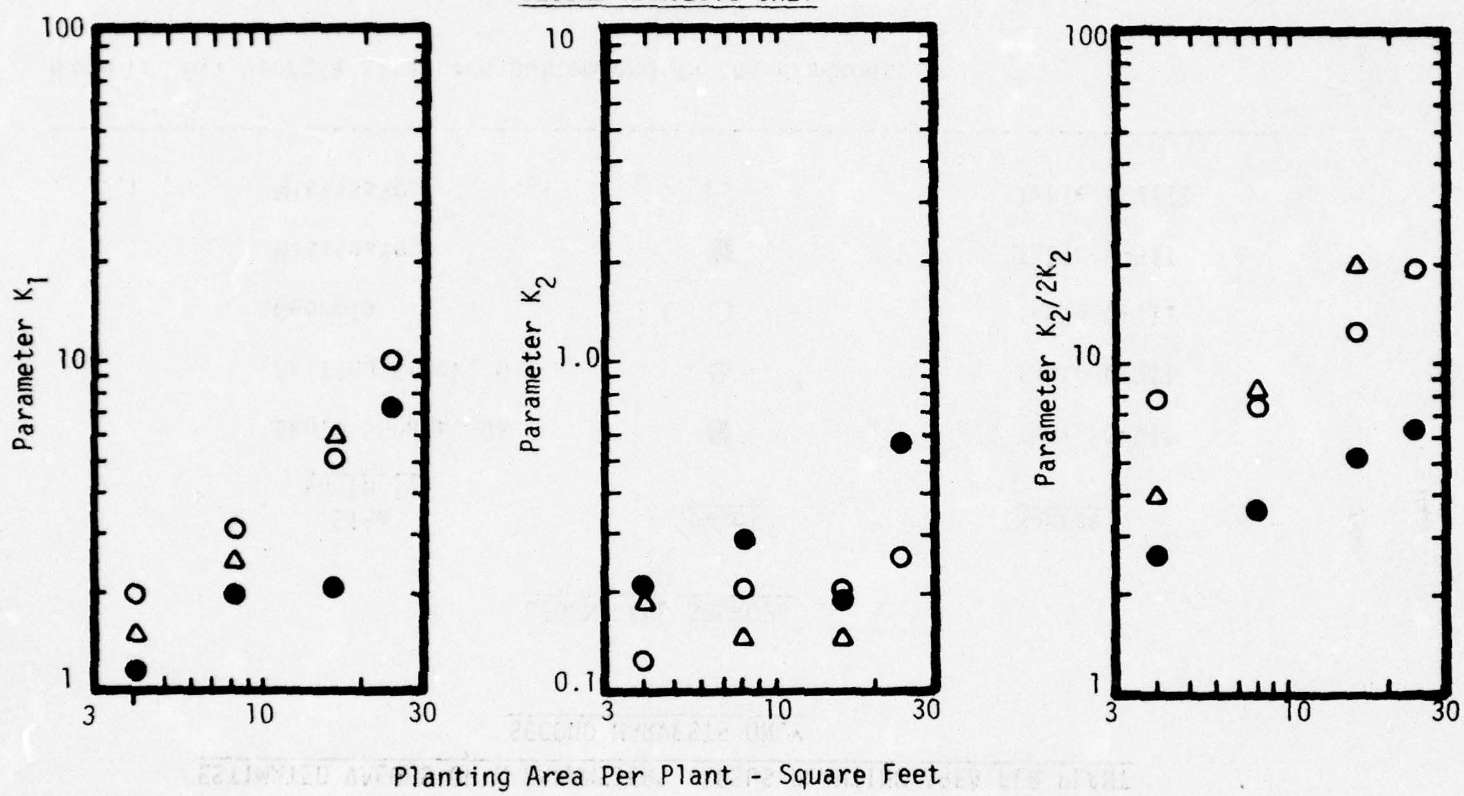


FIGURE C-XVII (continued)

FERTILIZED SYCAMORE

ESTIMATED VALUES OF K PARAMETERS VERSUS PLANTING AREA PER PLANT

SECOND HARVESTS ONLY

LEGEND AND SOURCES

Site (Note 1)	Symbol	Source
Georgia	●	Table C-VII
Georgia	△	Table C-VII
Georgia	○	Table C-VII

Note 1: All Georgia sites are bottomland in the Piedmont.

The uniformity of the slopes for first harvests and for second harvests revealed in Figure C-XVIII is significant. The slope of the regression lines measures the influence of spacing or crowding between plants on their rate of growth. It is remarkable that this effect is apparently so similar for first harvests from the species represented in the figure, and also for second harvests. It is to be noted that spacing has a stronger influence on yields from second than from first harvests--a not unexpected finding, because deciduous species generate several sprouts from their stumps after harvest and, consequently, being bushier than they were prior to the first harvest, fill the space between plants more quickly, thereby interfering with one another sooner than is likely before the first harvest.

IV.B.6.b. Dependence of the Growth Parameter on Species and Varieties. It is apparent from Figure C-XVIII for any given planting density that the growth parameter K_1 varies significantly from species to species. For instance, for first harvests at a planting density of about 6.5 square feet per plant, which is in the middle of the range of interest for Energy Plantations, the values of K_1 for the species shown in the figure are in the following order:

all hybrid poplars	0.52
hybrid poplar clone NE-388	0.64
cottonwood (P. deltoides)	1.33
fertilized sycamore	1.95

For second harvests, the estimates of K_1 for the species in the figure are:

hybrid poplar clone NE-388	3.99
fertilized sycamore	2.26
black cottonwood	1.40
unfertilized sycamore	1.35

TABLE C-IX

ESTIMATES OF THE CONSTANTS μ_1 AND μ_2 IN EQUATION C-17 FOR *FIRST HARVESTS* FROM A VARIETY OF DECIDUOUS SPECIES GROWN ON SEVERAL SITES WITH VARIOUS CULTURAL TREATMENTS

Species	Footnotes	Equations for K_1 Estimate	Estimates of μ_1 Mean Value	Estimates of μ_1 Standard Deviation	Estimates of μ_2 Mean Value	Estimates of μ_2 Standard Deviation
Cottonwood (*P. deltoides*)	1	C-12	0.34478	0.01066	0.72124	0.00716
Hybrid Poplars:						
NE 388	2	C-12	0.14537	0.00006	0.67621	0.00047
NE 388	3	C-12	0.18504	0.02445	0.69247	0.11835
NE 388	4	C-12	0.16257	0.01696	0.73294	0.10623
49	5	C-12	0.14976	0.00990	0.39786	0.05931
252	6	C-12	0.14716	0.00604	0.78659	0.03684
All clones	7	C-12	0.15608	0.01572	0.64032	0.09601
Sycamore:						
Fertilized	8	C-12	0.52137	0.07027	0.70469	0.06749
Low-yield Plantings	9	C-12	0.39554	?	0.43458	?
Reference 21	10	C-13	0.41465	0.16498	0.49420	0.15832
Reference 23	11	C-13	0.37983	0.01971	0.24782	0.02116

Footnotes:	Source	Site	Reference
1	Table C-V	Mississippi	10
2	Table C-V	Musser Farm, Pa.	1
3	Table C-V	Stone Valley, Pa.	17
4	Table C-V	See footnotes 2 & 3	1 and 17
5	Table C-V	Stone Valley, Pa.	17
6	Table C-V	Stone Valley, Pa.	17
7	Table C-V	All sites	1 and 17
8	Table C-V	Georgia and Mississippi	21 and 31
9	Table C-V	Georgia	23 and 26
10	Table C-VI	Georgia Piedmont bottomland	21
11	Table C-VI	Georgia Piedmont bottomland	23

These differences in the parameters K_1 may be due to several factors among which are the following:

- inherent differences in growth rate between species (the larger K_1 is, the greater the growth rate--see equation C-8);
- differences in growing conditions (soil and climate) between the sites represented by the data in Tables C-IX and C-X;
- differences in the degree to which the various species in Tables C-IX and C-X are adapted to their respective growth sites; and
- effect of using fertilizer.

Estimates have been made of the growth parameter K_1 as a function of planting density for the various hybrid poplar stands in Tables C-IX and C-X. The estimates, calculated from the appropriate μ values in the tables, are shown in Figure C-XIX. Note there are differences in the growth parameter K_1 (and hence also in the growth rate per plant) for the three varieties grown at Stone Valley, Pennsylvania, even though they were all grown simultaneously. These differences may be due to experimental variation, inherent differences between varieties, or to differences in the degrees of adaptation to the site. The difference in the parameter K_1 for clone NE 388 grown at two sites (Musser Farm and Stone Valley) could be due to experimental error, differences in the degree of adaptation to the sites, or differences arising from variations in the local conditions (soil and climate) between the sites. Experimental error can be ruled out as an important cause for variation, because the estimates of the growth parameter K_1 are based on plantings at several planting densities (see Table C-I) and on several harvests (see "Average Over" column in Tables C-V and C-VII). Unfortunately, there are insufficient data to separate and appraise the other effects.

TABLE C-X

ESTIMATES OF THE CONSTANTS μ_1 AND μ_2 IN EQUATION C-17 FOR *SECOND HARVESTS* FROM A VARIETY OF DECIDUOUS SPECIES GROWN AT SEVERAL SITES WITH VARIOUS CULTURAL TREATMENTS

Species	Footnotes	Equations for K_1 Estimate	Estimates of μ_1		Estimates of μ_2	
			Mean Value	Standard Deviation	Mean Value	Standard Deviation
Black Cottonwood	1	C-12	0.23383	0.07349	0.95461	0.17284
Hybrid Poplar NE 388	2	C-12	0.72162	0.18766	0.91384	0.28743
Sycamore-fert.						
-stumps, 1 Yr.old	3	C-12	0.24710	0.06135	1.04597	0.10530
-stumps, 1 Yr.old	4	C-12	0.54603	0.18294	0.86093	0.13425
-stumps, 2 Yr. old	5	C-12	0.35562	0.12466	0.98757	0.15950
-all stumps	6	C-12	0.36048	0.08565	0.97335	0.10102
Sycamore-Unfert.						
-stumps, 1 Yr.old	7	C-12	0.32236	?	0.84781	?
-stumps, 1 Yr.old	8	C-12	0.35431	0.07916	0.66557	0.09493
-all 1-Yr. old stumps	9	C-12	0.30812	0.12109	0.78887	0.15460
-stumps 1 & 2 Yr. old	10	C-12	0.02945	?	1.11832	?

Footnotes:	Source	Site	Reference
1	Table C-VII	Mt. Vernon, Wash.	19
2	Table C-VII	Musser Farm, Pa.	1
3	Table C-VII	Georgia Piedmont bottomland	23
4	Table C-VII	Georgia Piedmont bottomland	21
5	Table C-VII	Georgia Piedmont upland	29
6	Table C-VII	See footnotes 3, 4, & 5	21, 23 & 29
7	Table C-VII	Georgia - Skull Shoals	26
8	Table C-VII	Georgia - Falling Creek	26
9	Table C-VII	See footnotes 7 and 8	26
10	Table C-VII	Georgia Piedmont bottomland	32

Comparison of the growth parameters K_1 for second harvests from fertilized and unfertilized sycamore (lines B and E in Figure C-XVIII) grown in bottomland in the Georgia Piedmont suggests that fertilization could be responsible for a substantial part of the difference between the values in K_1 for first harvests for sycamore (fertilized-line C) and the two hybrid poplar entries (lines G and H), neither of which were fertilized.

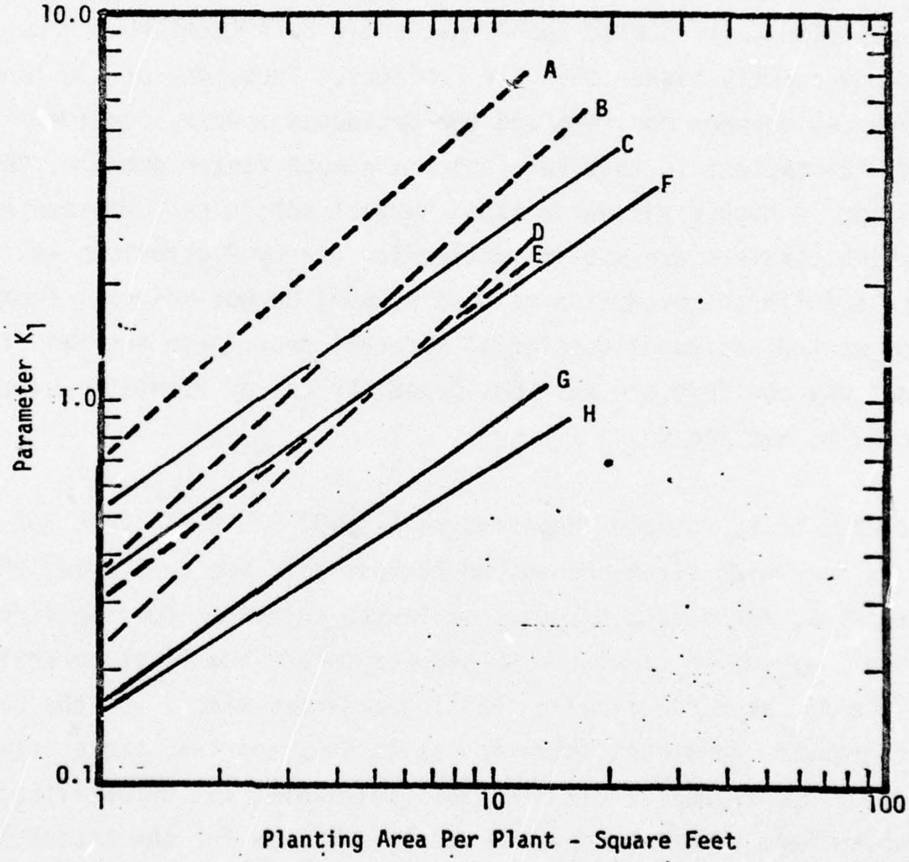
Significant differences in the growth rate of cottonwood varieties grown in the midsouth have been reported[34]. The data from this source have not been considered in the analysis of the parameter K_1 in Tables C-V through C-X and in Figures C-XII through C-XVIII, because they are not complete enough for inclusion. They do, however, support the conclusion with respect to hybrid poplars, to wit that there are differences in growth rate under the same growing conditions (common site, for instance) between varieties within a species.

While pines are of no interest for Energy Plantations, it is worth noting that experiments conducted in Florida[35] indicate breeding and selecting particular strains of slash pine may significantly improve growth rates and yields in pine plantations. This observation is further substantiation of the conclusion reached at the end of the preceding paragraph.

A note can be made at this point about the relative growth rates of deciduous species versus conifers. As can be seen in Table C-V, the growth parameters K_1 for slash and Choctawhatchee pines (fertilized and unfertilized) grown at a planting density of eighty square feet per tree are much smaller than that for Eastern cottonwood grown at seventy-two square feet per plant.

FIGURE C-XVIII

REGRESSION LINES CALCULATED USING EQUATION C-17 AND μ VALUES SHOWN IN TABLES C-IX AND C-X



LEGEND:

Table References - by Table Footnote Number

LINE	SPECIES	FIRST HARVESTS TABLE C-IX	SECOND HARVESTS TABLE C-X
A	Hybrid poplar - NE-388		2
B	Sycamore - fertilized		6
C	Sycamore - fertilized	8	
D	Black cottonwood		1
E	Sycamore - unfertilized		9
F	Cottonwood	1	
G	Hybrid Poplar - NE-388	4	
H	Hybrid Poplar - all clones	7	

By extrapolating the values of K_1 for sycamore and poplar to eighty square feet per plant, it is also found that the growth rates for these species are significantly higher than for conifers. Thus, one of the important differences between conifers and the deciduous species considered for Energy Plantations is that the latter are much faster growers, thereby resulting in higher yields on short harvest schedules. Another reason for which conifers are not attractive for Energy Plantations is that conifers (with the exception of pond pine[36]) do not resprout from their stumps as the deciduous species of interest do. These are two of the reasons why conifers are not considered for Energy Plantations (see also Appendix B, Section V).

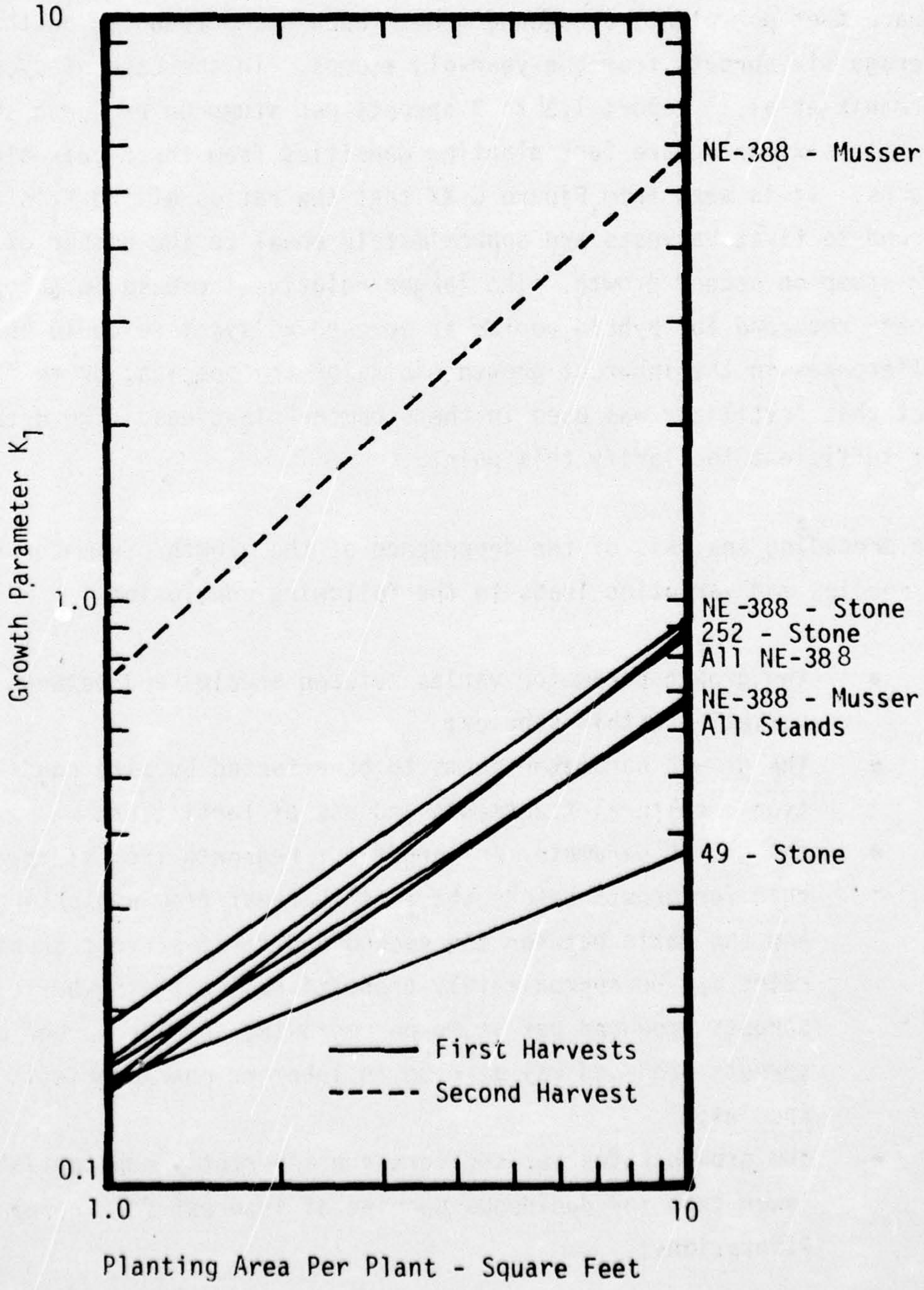
It is also to be noticed from Figures C-XVIII and C-XIX that for the species for which first and second-harvest data are available, the growth parameter K_1 for second harvests is larger than that for the first. The ratio of the growth parameter K_1 between second and first harvests can be expressed as a function of planting area per plant. On the basis of the regression constants shown in Tables C-IX and C-X, these relationships for hybrid poplar clone NE-388 (cultivated but unfertilized) grown at Musser Farm from one to three-year-old stumps for the second harvest and for fertilized sycamore (footnote 4 in Table C-X and 8 in table C-IX) regrown from one-year-old stumps are, respectively:

$$\frac{(K_1)_2}{(K_1)_1} = 4.96402A^{0.23763} \qquad \text{(C-21)}$$

$$\frac{(K_1)_2}{(K_1)_1} = 1.04730A^{0.15624} \qquad \text{(C-22)}$$

FIGURE C-XIX

ESTIMATED VALUES OF THE GROWTH PARAMETER K_1 FOR VARIOUS HYBRID POPLAR STANDS



These equations are plotted on Figure C-XX. The fact that second growth rates are higher than the first is not surprising as on second growth each stump develops several sprouts and, as a consequence, considerable bushiness. For instance, Bowersox[1] reports that at four square feet per plant, on second growth each stump produces on the average six sprouts from one-year-old stumps. In the case of sycamore, Kormanik et al.[21] report 1.5 to 3 sprouts per stump on regrowth at four to sixteen square feet planting densities from three-year-old stumps. It is seen from Figure C-XX that the ratios of the K_1's for second to first harvests are approximately equal to the number of sprouts per stump on second growth. The larger relative increase in second growth recorded for hybrid poplar as opposed to sycamore could be due to differences in the inherent growth habits of the species, or to the fact that fertilizer was used in the sycamore plantings. The data are not sufficient to clarify this point.

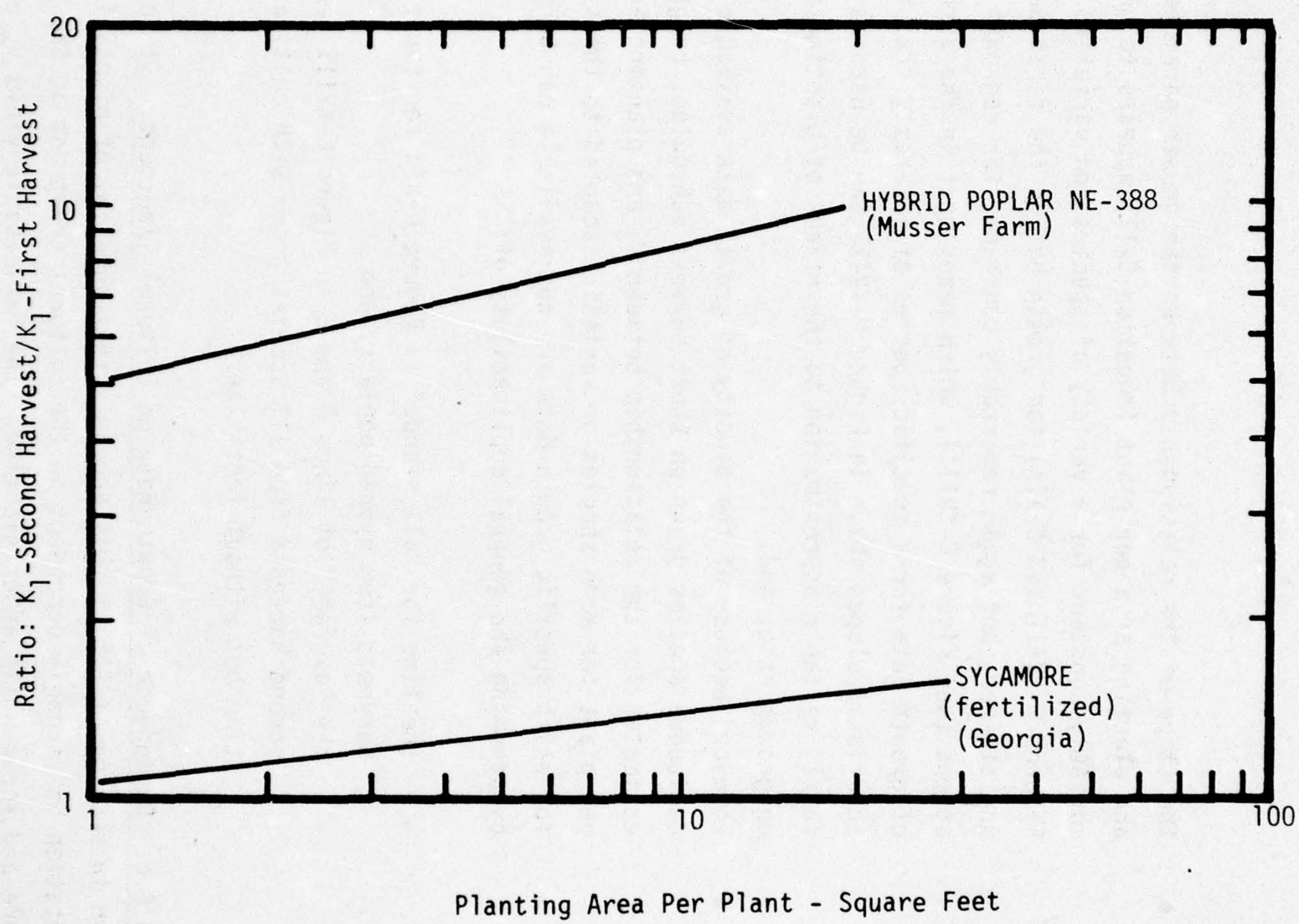
The preceding analysis of the dependence of the growth parameter K_1 on species and varieties leads to the following conclusions:

- the growth parameter varies between species and between varieties within species;
- the growth parameter seems to be affected by site conditions, cultural treatments and use of fertilizer;
- the growth parameter is larger for regrowth from stumps than for growth before the first harvest from a planting, and the ratio between the second and first-harvest growth rates may be approximately proportional to the number of sprouts produced per stump on regrowth, and the number of sprouts produced may also be an inherent characteristic of species;
- the growth rates for conifers are inherently substantially lower than for deciduous species of interest for Energy Plantations;

FIGURE C-XX

ESTIMATED RATIO OF GROWTH PARAMETERS K_1 FOR SECOND HARVESTS TO FIRST HARVESTS

HYBRID POPLAR CLONE NE-388 AND FERTILIZED SYCAMORE



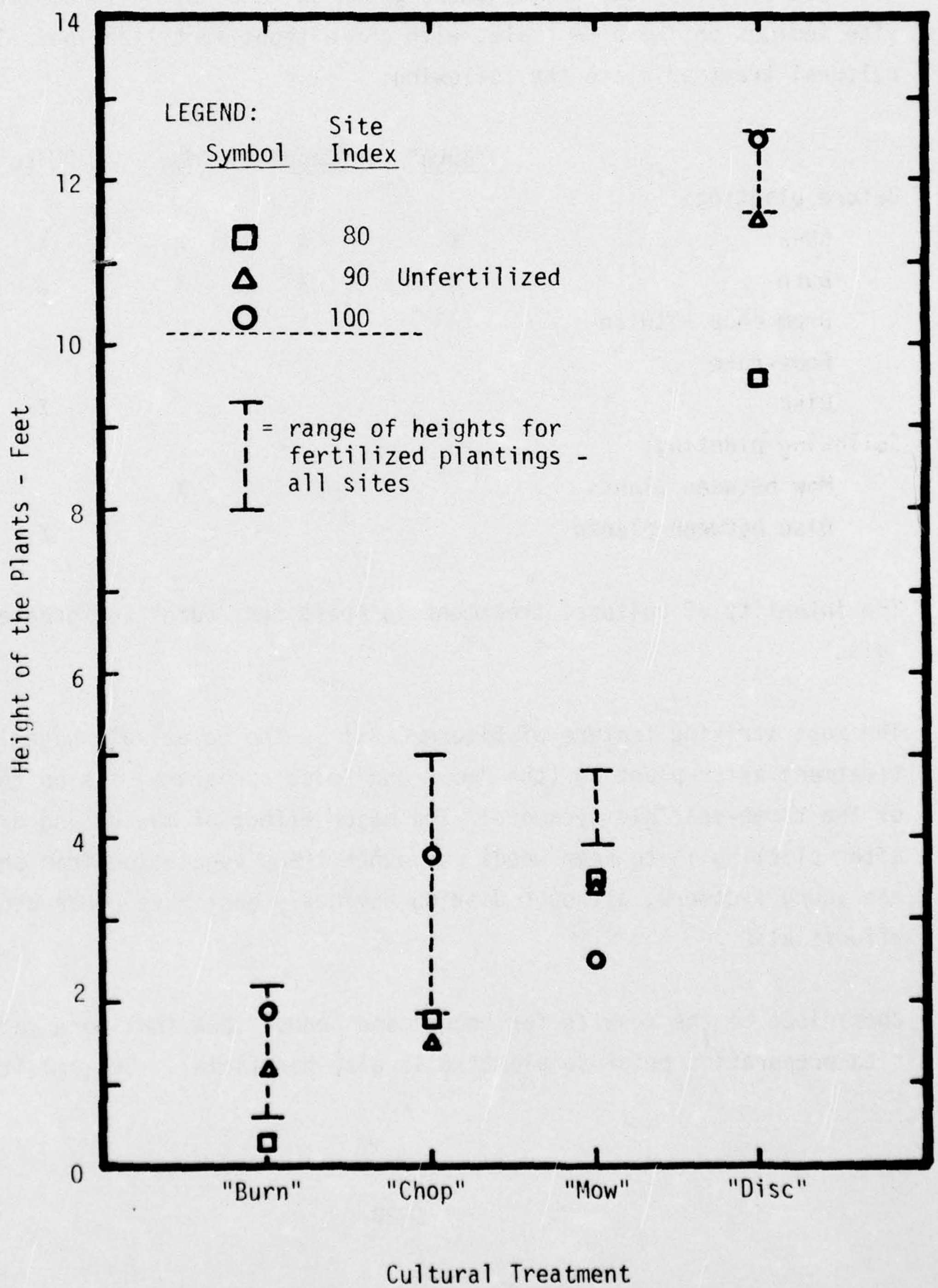
- the slope of the relationship between the growth parameter K_1 and planting area per plant (equation C-17) appears to be remarkably constant for a variety of species and varieties (see Figures C-XVIII and C-XIX) for growth before the first harvest, and steeper, but again remarkably constant, for regrowth from stumps (see Figure C-XVIII), which means that in the absence of growth data for a specific species of interest, the characteristic slopes shown in Figure C-XVIII can be used as a fairly reliable approximation to the effect of planting area on growth rate; and,
- however, because of the paucity of growth data available for deciduous species grown on short harvest schedules, rough estimates for the relationship between K_1 and planting area per plant for some species or varieties adapted to the site for which specific growth data are not available can be made by assuming the general applicability of:

  - the line for "all stands" in Figure C-XIX for first harvests from hybrid poplars; and
  - the "average" of lines D and E in Figure C-XVIII for second harvests from all species grown with cultivation but without fertilizer.

IV.B.6.c. Dependence of Growth Rate on Cultural Treatment. It has been shown in section IV.A.5 of this appendix that survival of plants in a plantation is strongly dependent on the cultural treatment at the site before and, for a while, after planting. The harvestable yield y_n of plant material per plant is similarly dependent on cultural treatment--a point well illustrated by the data in Figure C-XXI for sycamore grown in

FIGURE C-XXI

HEIGHT OF THREE-YEAR-OLD SYCAMORE AS A FUNCTION OF CULTURAL TREATMENT, FERTILIZATION AND SITE INDEX



Source: Reference 16 and 22.

Bainbridge, Georgia by International Paper Company[16,22]. These data show the influence of each of four cultural programs on the height attained by three-year-old sycamore grown on land having three different site indices on the pine scale, with and without fertilization. The cultural treatments are the following:

	"Burn"	"Chop"	"Mow"	"Disc"
Before planting:				
Shear	X	X	X	X
Burn	X	X	X	X
Drum chop - twice		X		
Root-rake			X	
Disc				X
Following planting:				
Mow between plants			X	
Disc between plants				X

The intensity of cultural treatment is least for "burn" and greatest for "disc".

The most striking feature of Figure C-XXI is the relatively huge impact treatment after planting (the "mow" and "disc" programs) has on the height of the three-year-old sycamore. The major effect of mowing and disking after planting is to keep weeds and other tramp vegetation from shading the young sycamore, although disking obviously must have other beneficial effects also.

Comparison of the results for "burn" and "chop" show that more intense site preparation prior to planting is also beneficial. But simultaneous reference to Table C-XI and Figure C-XXI suggests root-raking (a step in the "mow" sequence in Figure C-XXI) before planting has only a relatively small effect compared with mowing or disking after planting. The same conclusion appears justified with respect to the relative benefit between disking before and after planting.

Results similar to those summarized in Figure C-XXI are reported by International Paper Company[16,22] for sweetgum at Bainbridge and for sycamore and sweetgum at the other sites (see page C-32) in the paper company's experimental program. Comparable experiments in Kansas[11] on cottonwood, sycamore, Russian olive, hackberry and green ash show that in all cases weed control through cultivation gives better growth per plant than does either mowing or chemical weed control.

The same remarks which were made about the effect of chemical weed-control agents on plant survival (see page C-36) also apply to plant growth rate.

No quantitative data have been found for assessing the effect of a cover crop used for weed control on the growth rate of deciduous species. Experiments along these lines are underway in Georgia on sycamore[26], but no results have been reported yet. Data have been reported, however, on the influence of a cover crop on the growth rate of slash pine[35,36,37]. The data indicate that in most cases for unfertilized sites, the use of a cover crop resulted in a loss of about ten percent of the yield achieved when disking is used for weed control. On fertilized sites, use of a cover crop for weed control increased the yield by about six percent over that achieved when disking was used for weed control. It should be stressed that these conclusions are not general and were found to vary between strains of slash pine.

The data available on the effect of cultural treatment on growth rate leads to the following conclusions:

- site preparation prior to planting, which includes removing plant material over a few inches above ground level, followed by disking contributes to a higher growth rate of the planted species;
- weed control after planting and until the planted species is well established contributes markedly to the growth rate of the planted species; and
- disking appears to be the best means for weed control, although use of a cover crop may be another effective means.

IV.B.6.d. Influence of Fertilization on Growth Rate. There are no definitive results showing the maximum benefits of various fertilization treatments on the growth rate of deciduous tree species grown on short harvest schedules. In a few cases, fertilization has been shown to be beneficial to growth and yield of species of interest for Energy Plantations. The amount of dry plant material produced by sixty-four sycamores produced from a mixture of four clone types grown from April to October with application of a Hoagland nutrient solution, as a function of the concentration of the nutrient solution is shown in Figure C-XXII. It will be seen that the amount of plant matter produced increases at first with solution concentration and then seems to decrease[38]. The response of sycamore to fertilization is also indicated in Table C-VII, where it is seen that all the growth parameters K_1 for fertilized experiments are larger than those for unfertilized experiments. The same trend is apparent in Figure C-XVIII. It has been reported that the growth rate of black cottonwood responds to fertilization[25]. In this case, application of 16-16-16 fertilizer increased the yields from the first harvest from a two-year-old planting and from a second harvest two years later by between thirty and forty percent.

TABLE C-XI

EFFECT OF SITE PREPARATION PRIOR TO PLANTING ON GROWTH OF PINES IN SANDY SOILS IN THE CAROLINAS, FLORIDA AND GEORGIA FIFTEEN YEARS AFTER PLANTING

Site Preparation Procedure	Harvestable Weight per Tree Oven-Dry Pounds
No preparation	4.2
Burning only	5.6
Burn and root-rake	9.6
Burn and B.S.W.[1] twice	16.4
Burn and B.S.W.[1] once	23.8
Burn, root-rake and disc	27.6
Burn and chop once	39.8
Burn and chop twice	55.9

Source: Reference 7 from which the tree heights and breast-high diameters given have been converted into oven-dry weights by the relation:

$$\text{weight} \simeq 0.1018\ D^2\ H$$

where D is the diameter in inches of the tree trunk at breast height, and H is the tree height in feet.

Note 1: A land-clearing machine having a sharp blade mounted like a bulldozer blade which shears stems protruding above the ground.

The heights of three-year-old sycamore and sweetgum grown without fertilization and with application of four hundred pounds per acre of 10-20-10 fertilizer in plots having three different site indices are shown in Figure C-XXIII. The plots were given the "disc" (see page C-88) cultural treatment. The data in this figure indicate, at least for the specific fertilization schedule followed, that:

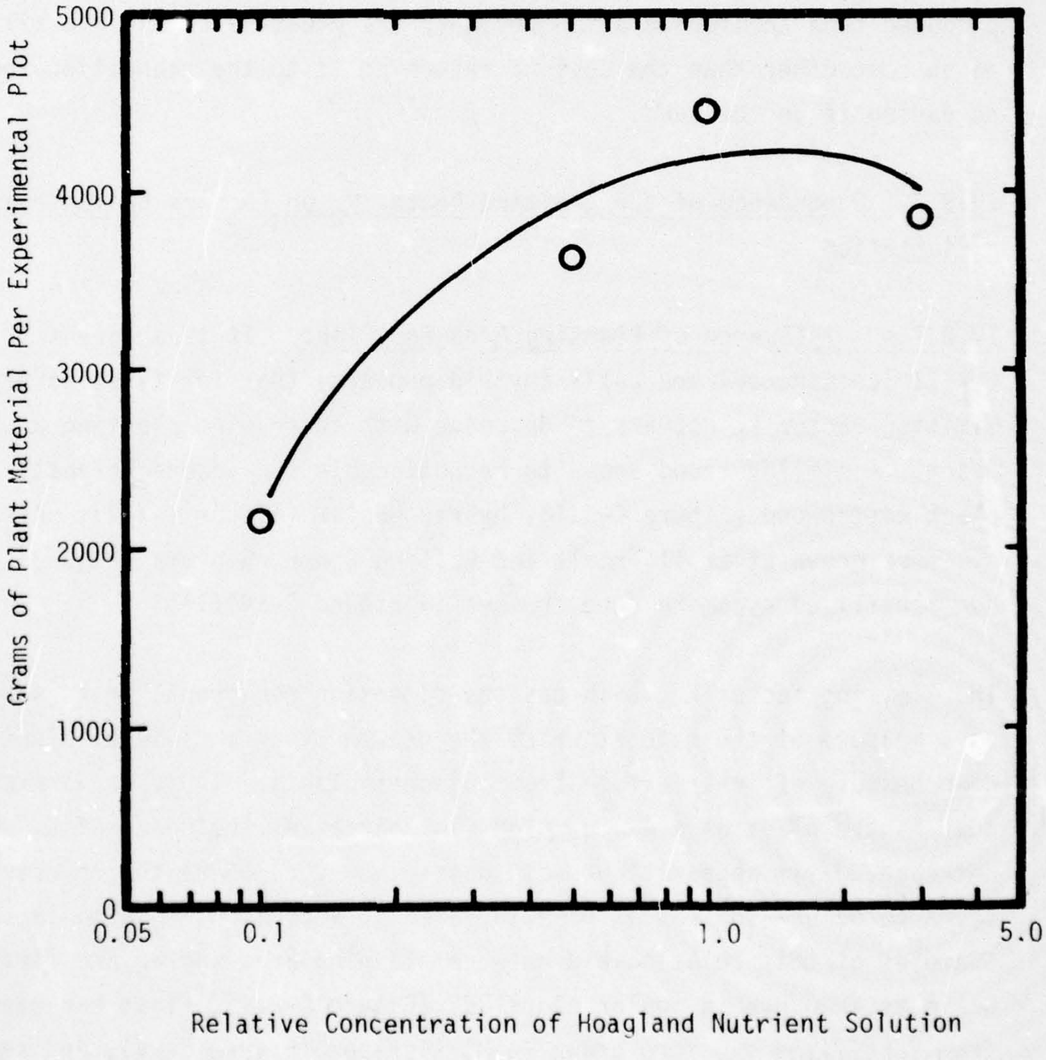
- growth of sycamore responds noticeably to fertilizer at the sites having indices of eighty and ninety, but not significantly at the site where the index is one hundred--in fact, fertilizer as used in these experiments[16,22] caused all three sites to be about equally productive for sycamore;
- growth of sweetgum was significantly increased by fertilizer at the site having an index of eighty, but statistically insignificant effects (according to references 16 and 22) were produced by fertilizer at the sites having indices of ninety and one hundred; and
- the response to fertilization depends on the species--the reponse of sycamore is larger than that of sweetgum--comparative tests for loblolly pine (not shown in Figure C-XXIII, but see reference 16) show no effect from fertilizer.

However, the effect of fertilizer is more complicated than these results suggest. For instance, the response of sycamore to fertilizer at a given *site index was statistically significant at only two of the localities* (see page C-32) at which these experiments were carried out[16,22]. The reason for the lack of response at many of the sites is unknown. It may, however, be that the factor limiting growth is something other than nutrient availability provided by the fertilizer. It might be moisture, for example.

FIGURE C-XXII

PLANT MATERIAL PRODUCTION FROM CERTAIN SYCAMORE STRAINS GROWN WITH APPLICATION OF HOAGLAND NUTRIENT SOLUTIONS OF VARIOUS CONCENTRATIONS

(Source: Reference 38)



Application of treated city sewage to tree plantations has also been shown to result in improved yields as compared to the yields at unfertilized sites[27]. This finding is of particular interest for plantations from which the plant material is to be used for making synthetic natural gas by anaerobic fermentation. It indicates that the sludge produced from the fermentation probably has great value as a fertilizer at no cost other than the cost of returning it to the plantation and spreading it on the land.

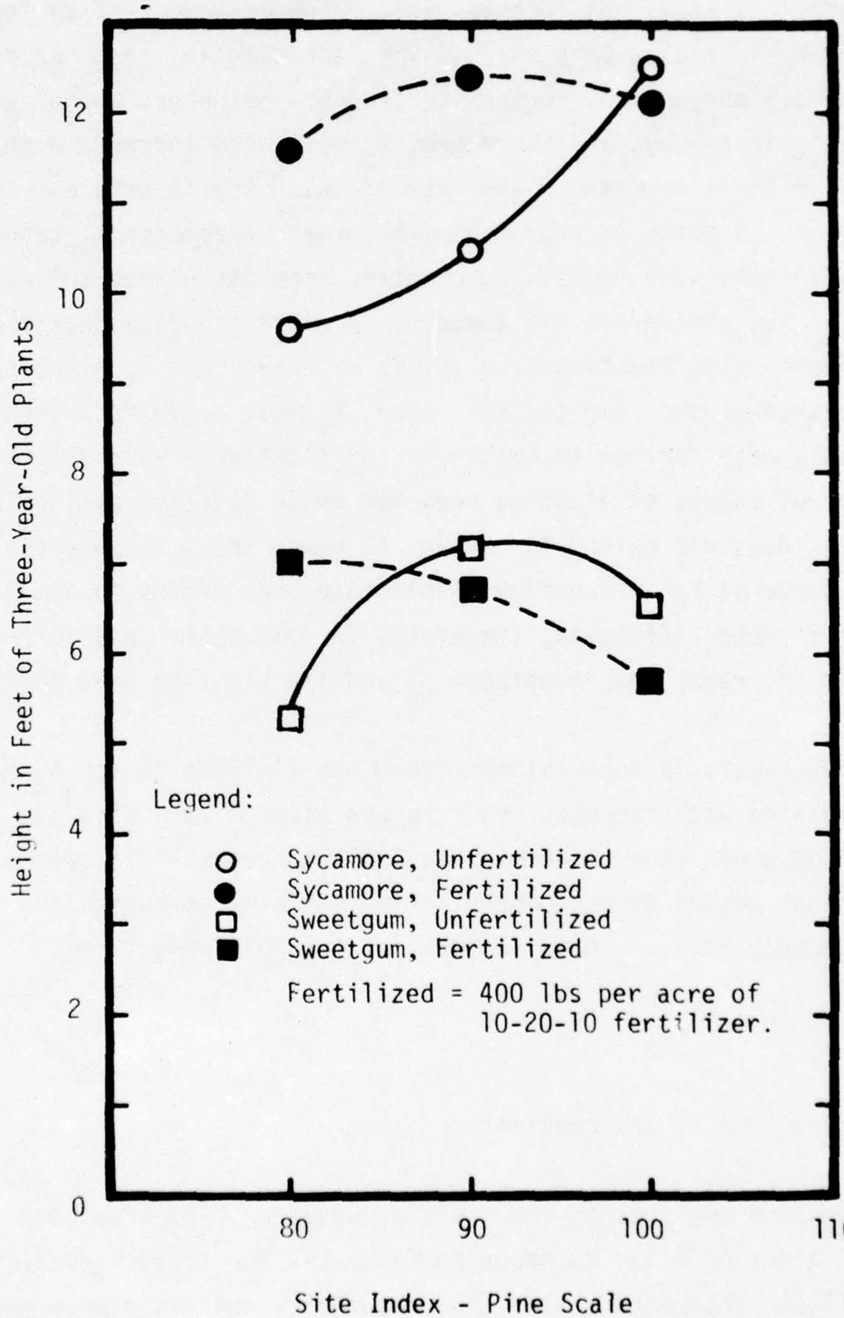
IV.B.7. Dependence of the Limiting Factor K_2 on Factors Characterizing a Plantation.

IV.B.7.a. Influence of Planting Area Per Plant. It is apparent in Figures C-XIII (cottonwood) and C-XIV (hybrid poplars) that for first harvests, the limiting factor K_2 appears to decrease with increasing planting area per plant. A similar trend seems to be noticeable for second harvests from black cottonwood (Figure C-XII), hybrid poplar (Figure C-XIV), unfertilized sycamore grown at Skull Shoals and Falling Creek, Georgia (Figure C-XVI), and fertilized sycamore (the crosses in Figure C-XVIII).

The limiting factor K_2, which has the dimension reciprocal years squared, is a measure of the rate at which the growth of an individual plant slows down because of interference from adjacent plants. Thus, it is expected that as the planting area per plant is increased, the value of K_2 should decrease. There appear to be some cases, however, where the reverse seems to occur--that is, as planting area is increased, K_2 also increases. Examples of this relationship between planting area and K_2 are first harvests from hybrid poplar clone 252 (Figure C-XIV), first harvests from fertilized sycamore grown in Mississippi (Figure C-XV), and second harvests from fertilized sycamore (Figure C-XVII).

FIGURE C-XXIII

INFLUENCE OF FERTILIZER ON THE HEIGHT OF THREE-YEAR-OLD SYCAMORE AND SWEETGUM GROWN WITH "DISC" CULTURAL TREATMENT AT BAINBRIDGE, GEORGIA



Source: References 16 and 22.

Although any tendency for K_2 to increase with planting area per plant is unexpected, it is not inconceivable. For instance, if the growth parameter K_1 increases very sharply with the planting area per plant, the plant may encounter interference from its neighbors sooner as planting area is increased, and therefore, K_2 must also increase with planting area if it is to measure the rate at which the interference develops. However, as noted on page C-58, the growth parameter K_1 cannot increase indefinitely with increasing planting area per plant, and nor can the factor K_2. Therefore, in these cases where the data indicate that K_2 increases with planting area, it is expected that as planting area is increased beyond some certain value, K_2 will begin to increase less rapidly with further increases in the planting area. Unfortunately, the range of values of planting area for which data are available for computing K_2 does not extend far enough to reach the point where the slope of the curve of K_2 as function of planting area begins to decline. There will be some difficulty, therefore, in some cases in interpreting and using the relationship between K_2 and the planting area per plant.

Because there is some evidence that the limiting factor K_2 may be correlated with the planting area per plant A by a straight line on log-log graph paper (see Figures C-XII through C-XVII) for a number of combinations of species and planting site, an approximation to the dependency between these factors has the following form:

$$K_2 = \eta_1 A^{\eta_2} \qquad \text{(C-23)}$$

where η_1 and η_2 are constants.

Regression analyses on the basis of equation C-23 have been made between the values of A and K_2 shown in Table C-V for first harvests and Table C-VII for second harvests. The results of these analyses are shown in Tables C-XII and C-XIII, respectively.

TABLE C-XII

ESTIMATES OF THE CONSTANTS η_1 AND η_2 IN EQUATION C-23 FOR *FIRST HARVESTS* FROM A VARIETY OF DECIDUOUS SPECIES GROWN AT SEVERAL SITES WITH VARIOUS CULTURAL TREATMENTS

Species	Footnotes	Estimates of η_1 Mean Value	Estimates of η_1 Standard Deviation	Estimates of η_2 Mean Value	Estimates of η_2 Standard Deviation
Cottonwood	1	(0.00469)	(0.00233)	(+0.19069)	(0.11096)
(*P. deltoides*)	2	0.04157	0.08644	-0.34881	0.31540
Hybrid Poplars					
NE-388	3	0.03462	0.00439	-0.22994	0.14140
NE-388	4	0.05771	0.01517	-0.20036	0.23348
All NE-388	5	0.04387	0.01014	-0.11357	0.22099
49	6	0.06589	0.00538	-0.28030	0.07326
252	7	(0.05023)	(0.01056)	(+0.05915)	(0.18737)
All clones	8	0.05009	0.00661	-0.09181	0.12177
Sycamore:					
Reference 31	9	(0.00593)	(0.00278)	(+0.68567)	(0.20992)
All plantings	10	0.07244	0.13028	-0.40257	0.070324

Footnotes	Source	Site	Reference
1*	Table C-V	Mississippi	10
2*	"	"	10
3	"	Musser Farm. Pa.	1
4	"	Stone Valley, Pa.	17
5	"	See footnotes 3 & 4	1 and 17
6	"	Stone Valley, Pa.	17
7	"	" " "	17
8	"	See footnotes 5, 6, & 7	1 and 17
9	"	Mississippi	31
10	"	Georgia and Mississippi	21, 23, 26 and 38

*see also text, page C-98.

In Table C-XII for first harvests, the values in parenthesis for cottonwood, poplar and sycamore correspond to regression lines for K_2 having positive slopes. The values of the η's in these cases are doubtful. The doubtful values for cottonwood were obtained using the three points for the smaller planting areas per plant used to obtain the K_1 regression line for cottonwood. The other set of values for cottonwood was obtained using all available data points.

It is apparent from Table C-XIII that two of the sycamore cases display K_2-versus-A lines with positive slopes. The values shown for fertilized sycamore - all stumps result from regression analysis of all the data for fertilized sycamore. This case also displays a positive slope. The only potentially useful K_2-versus-A line for sycamore-fertilized is that for two-year-old stumps (reference 29).

It should also be noted that in most cases the standard deviations for the η estimates are very large--amounting in some instances to more than one hundred percent of the η values.

The regression lines for the limiting factor K_2 defined in Tables C-XII and C-XIII are shown in Figure C-XXIV. The line for black cottonwood is not shown because the natural habitat for this species is outside the localities likely to be of interest for plantations at troop training centers.

The ratios of the values of the limiting factor K_2 for second and first harvests for hybrid poplars clone NE-388 and fertilized sycamore are given, respectively, by:

$$\frac{(K_2)_2}{(K_2)_1} = 9.8159\ A^{-0.18853} \tag{C-24}$$

TABLE C-XIII

ESTIMATES OF THE CONSTANTS n_1 AND n_2 IN EQUATION C-23 FOR *SECOND HARVEST* FROM A VARIETY OF DECIDUOUS SPECIES GROWN AT SITES WITH VARIOUS CULTURAL TREATMENTS

Species	Footnotes	Estimates of n_1		Estimates of n_2	
		Mean Value	Standard Deviation	Mean Value	Standard Deviation
Black Cottonwood	1	0.06755	0.04008	-0.08194	0.31460
Hybrid Poplar NE-388	2	0.43082	0.02511	-0.30210	0.06510
Sycamore-fertilized:					
-stumps 1 year old	3	(0.11938)	(0.11919)	(+0.37622)	(0.35909)
-stumps 1 year old	4	(0.07992)	(0.02264)	(+0.37122)	(0.11406)
-stumps 2 years old	5	0.22952	0.04925	-0.17427	0.09882
-all stumps	6	(0.10678)	(0.04532)	(+0.30050)	(0.17380)
Sycamore-unfertilized:					
-stumps 1 year old	7	0.47207	?	-0.28971	?
-stumps 1 year old	8	0.35710	0.21174	-0.54831	0.24109
-all 1-year-old stumps	9	0.28285	0.31107	-0.28924	0.38303

Footnotes	Source	Site	Reference
1	Table C-VII	Mt. Vernon, Wash.	19
2	"	Musser Farm, Pa.	1
3	"	Georgia Piedmont Bottomland	23
4	"	Georgia Piedmont Bottomland	21
5	"	Georgia Piedmont Upland	29
6	"	See footnotes 3, 4, & 5	21, 23 & 29
7	"	Georgia - Skull shoals	26
8	"	Georgia - Falling Creek	26
9	"	See footnotes 7 and 8	26

$$\frac{(K_2)_2}{(K_2)_1} = 3.16841\ A^{-0.2283} \tag{C-25}$$

Equation C-24 for hybrid poplar clone NE-388 is computed from the estimates of η_1 and η_2 in Table C-XIII (footnote 2) and those in Table C-XII (footnote 5). Equation C-25 for fertilized sycamore is computed from the values for η_1 and η_2 for two-year-old stumps in Table C-XIII (footnote 5) and those for all plantings in Table C-XII (footnote 10).

The fact that K_2 is larger for the second harvest than for the first is not surprising. After the first harvest, each stump grows several sprouts which occupy the space allotted to each plant sooner when each plant has only one stem than prior to the first harvest.

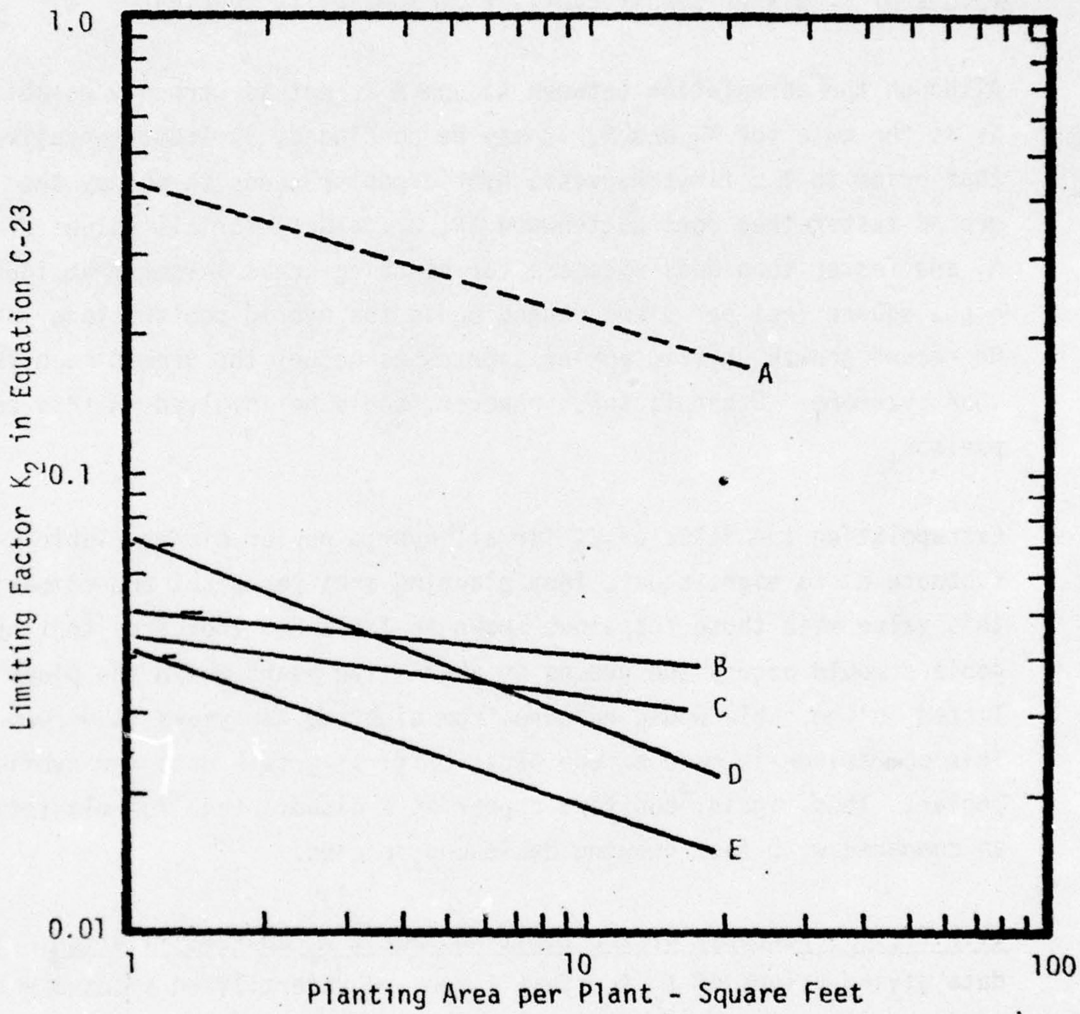
The preceding analysis of the dependence of the limiting factor K_2 on the planting area per plant A can be summarized as follows:

- there appears to be a linear dependence between the limiting factor K_2 and the planting area per plant A on a log-log plot at low values of A for first and second harvests;
- the correlation between K_2 and A is not as well established as is the case for K_1 and A--in fact, in some cases, the expected decrease of K_2 with increasing A is reversed; and
- the K_2 values for the second harvest are larger than those for the first, as is to be expected from the fact that plants occupy their assigned spaces more quickly after the first harvest than they do prior to it.

IV.B.7.b. Dependence of the Limiting Factor K_2 on Species and Varieties. It is apparent from Figure C-XXIV that, for a given planting area, the

FIGURE C-XXIV

REGRESSION LINES CALUCLATED USING EQUATION C-23
AND THE VALUES SHOWN IN TABLES C-XII and C-XIII



LEGEND

A	=	Hybrid poplar-NE-388, second harvest, Table C-XIII, footnote 2.
B	=	Hybrid poplar-all clones, first harvest, Table C-XII, footnote 8.
C	=	Hybrid poplar-all NE-388, first harvest, Table C-XII, footnote 5.
D	=	Sycamore-all plantings, first harvest, Table C-XII, footnote 10.
E	=	Cottonwood (*P. deltoides*), first harvest, Table C-XII, footnote 2.

values of K_2 differ significantly from species to species.

Although the correlation between K_2 and A is not as strongly established as is the case for K_1 and A, it may be concluded, at least tentatively, that prior to the first harvest, hybrid poplar tends to occupy the ground faster than does cottonwood (*P. deltoides*) for all values of A, and faster than does sycamore for planting areas larger than four to eight square feet per plant depending on the hybrid poplar clone involved. On second growth, hybrid poplar appears to occupy the ground much faster than sycamore. Other factors, however, could be involved in this comparison.

Extrapolating the value of K_2 for all hybrid poplar clones (Table C-XII, footnote 8) to eight square feet planting area per plant and comparing this value with those for pines shown in Table C-V indicates that hybrid poplars would occupy the ground in about five years while the pines listed in the table would require from eight to ten years to occupy it. This comparison is made on the basis of first-growth data for hybrid poplar. Thus, again, conifers appear at a disadvantage for plantations as compared with fast-growing deciduous species.

<u>IV.B.7.c. Dependence of the Limiting Factor K_2 on Fertilization</u>. The data giving values of K_2 for fertilized and unfertilized sites are rather limited--but see sycamore and slash pine in Table C-V, for first harvests, sycamore in Tables C-VII and C-VIII for second harvests. In most cases, the values of K_2 for a given area per plant are smaller for the unfertilized cases, which means it takes more time for unfertilized plants to occupy the ground. This is consistent with the data concerning the increase in the rate of growth K_1 with fertilization (see section IV.B.6.d).

IV.B.8. Dependence of the Asymptotic Yield $K_1/2K_2$ on Factors Characterizing a Plantation.

IV.B.8.a. Dependence on Planting Area per Plant. It is apparent from Figure C-XII for black cottonwood, Figure C-XIII for cottonwood, Figure C-XIV for hybrid poplars, Figure C-XVI for unfertilized sycamore and from Figure C-XVII for fertilized sycamore that the asymptotic yield per plant $K_1/2K_2$ increases as the planting area per plant A increases. Among the data available, there is only one case where there is no clear relationship between $K_1/2K_2$ and A--that is, for first harvests from sycamore (Figure C-XV). The asymptotic yield per plant is the maximum yield achievable by a particular species under given conditions (planting area, cultural treatment and so forth) when n in equation C-8 approaches infinity. It is not surprising that as A is increased, $K_1/2K_2$ also increases because more sun, nutrients, and water are available to each plant.

As is the case for K_1, the increase in $K_1/2K_2$ with increasing A cannot go on indefinitely, because if it could, a completely isolated plant would continue to grow without letup. It is well known that such is not the case. Therefore, it is to be expected that $K_1/2K_2$ will depend on A in much the same way as K_1 does (see equation C-14). The linear dependence between $K_1/2K_2$ and A on a log-log scale is an approximation valid for low values of A as is the case for K_1.

Regression analyses have been made between the values of $K_1/2K_2$ and A shown in Tables C-V and C-VII using an equation of the following form

$$\frac{K_1}{2K_2} = \gamma_1 A^{\gamma_2} \qquad \text{(C-26)}$$

The results of these analyses are shown in Tables C-XIV and C-XV, respectively. For first and second harvests, the standard deviations on γ_1 and γ_2 for hybrid poplars are of the order of fifteen to twenty percent of the value of these parameters. For first harvests for cottonwood (*P. deltoides*) the data are spread widely (see Figure C-XIII), which is reflected by an abnormally high value of γ_1 (compared with γ_1 for poplar and sycamore). The standard deviation on γ_1 is also very high. A somewhat similar situation is seen for first harvests from fertilized sycamore--high standard deviations on γ_1 and γ_2.

The regression lines represented by several of paired values of γ_1 and γ_2 are plotted in Figure C-XXV. It should be seen that there are significant differences between species.

The last set of data in Table C-XIV--cottonwood and hybrid poplars-unfertilized--is based on a regression analysis of the hybrid poplar and eastern cottonwood data from Table C-V. The data points used and the resulting regression line are plotted on Figure C-XXVI. As was pointed out earlier, the regression analysis of the cottonwood data led to rather high values for the γ's at low values of A-see Table C-XIV and Figure C-XXV. This could be due to the fact that the data available are rather scattered and valid for relatively high values of A. These factors could lead to a large uncertainty on the value of $K_1/2K_2$ on extrapolation to the values of A of interest for Energy Plantations. As is apparent in Figure C-XXVI, however, the data for hybrid poplar (at low values of A) and for cottonwood (at high values of A) appear to be reasonably well in line; therefore, a regression line generated on the basis of both sets of data would be a better and more reliable approximation for $K_1/2K_2$ at intermediate values of A (eight to twenty square feet per plant) than a line based on either the

TABLE C-XIV

ESTIMATES OF THE CONSTANTS γ_1 AND γ_2 IN EQUATION C-26 FOR *FIRST HARVESTS* FROM A VARIETY OF DECIDUOUS SPECIES GROWN AT SEVERAL SITES WITH VARIOUS CULTURAL TREATMENTS

Species	Footnotes	Mean Value	Standard Deviation	Mean Value	Standard Deviation
Cottonwood	1	(36.73500)	(17.01633)	(0.53079)	(0.10387)
(*P. deltoides*)	2	6.43751	9.54787	0.96128	0.25287
Hybrid Poplars:					
NE-388	3	2.09933	0.26520	0.90615	0.14080
NE-388	4	1.60321	0.33236	0.89283	0.18487
All NE-388	5	1.85213	0.27255	0.84651	0.14141
49	6	3.58977	0.50158	0.67816	0.12508
252	7	1.46481	0.36109	0.72743	0.21920
All Clones	8	1.55815	0.24168	0.73212	0.14303
Sycamore-fertilized	9	2.56559	4.99478	1.16038	0.73967
Cottonwood and Hybrid poplar-unfertilized	10	0.98358	0.14905	1.30558	0.06785

Footnotes	Source	Site	Reference
1	Table C-V	Mississippi	10
2	"	Mississippi	10
3	"	Musser Farm, Pa.	1
4	"	Stone Valley, Pa.	17
5	"	See footnotes 3 and 4	1 and 17
6	"	Stone Valley, Pa.	17
7	"	Stone Valley, Pa.	17
8	"	See footnotes 5, 6, and 7	1 and 17
9	"	Georgia and Mississippi	21, 23, 26 & 31
10	"	Mississippi and Pennsylvania	1, 10 & 17

FIGURE C-XXV

REGRESSION LINES CALCULATED USING EQUATION C-26 AND THE γ VALUES SHOWN IN TABLES C-XIV AND C-XV

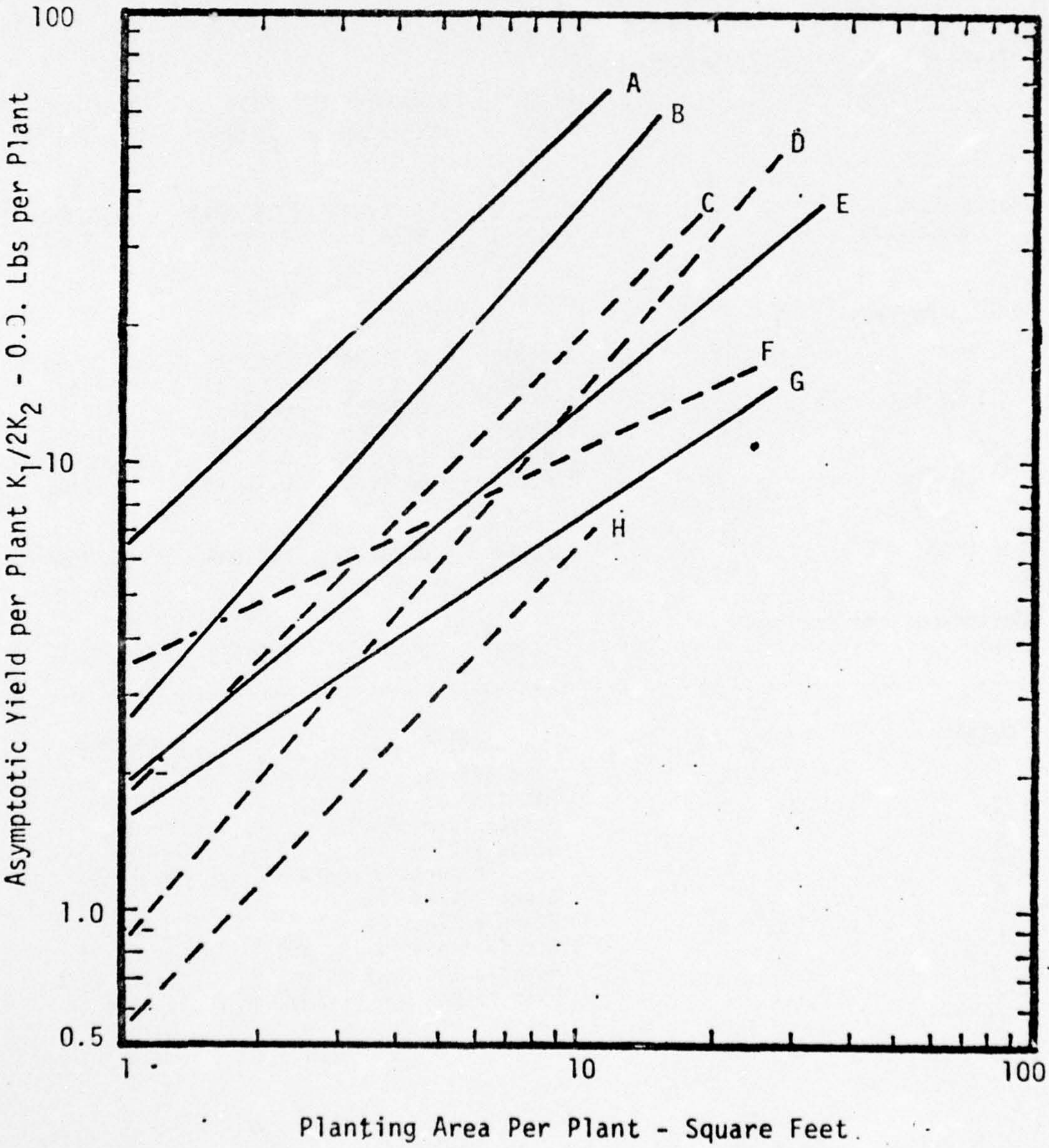


FIGURE C-XXV

REGRESSION LINES CALCULATED USING EQUATION C-26 AND THE γ VALUES SHOWN IN TABLES C-XIV AND C-XV

LEGEND

A = Cottonwood (*P. deltoides*), first harvest
Table C-XIV, footnote 2.

B = Sycamore - fertilized, first harvest,
Table C-XIV, footnote 9.

C = Black cottonwood, second harvest,
Table C-XV, footnote 1.

D = Hybrid poplar clone NE-388, second harvest,
Table C-XV, footnote 2.

E = Hybrid poplar, all NE-388, first harvest,
Table C-XIV, footnote 5.

F = Sycamore - fertilized, second harvest,
Table C-XV, footnote 4.

G = Hybrid poplar, all clones, first harvest,
Table C-XIV, footnote 8.

H = Sycamore - unfertilized, second harvest,
Table C-XV, footnote 10.

poplar or cottonwood data alone. The result of the regression analysis is the "cottonwood and hybrid poplar - unfertilized" line plotted on Figure C-XXVI.

It is apparent that individual $K_1/2K_2$ values for aspen and sycamore, both unfertilized, are reasonably close to the cottonwood - hybrid poplar line shown in Figure C-XXVI, thus lending support to the general validity of this line. The Choctawhatchee pine point at eighty square feet is significantly below the cottonwood - hybrid poplar line. This is not surprising because the sandhill site in Georgia in which these pines were grown is nowhere near as productive as the sites in Mississippi and Pennsylvania on which the cottonwood and hybrid poplar were grown.

Thus, it is suggested that for varieties for which a K_1/K_2-versus-A correlation for first growth is not available (lack of data or doubtful data), the unfertilized cottonwood - hybrid poplar relation shown in Figure C-XXVI be used, providing the growing conditions are reasonably good and the variety considered is adapted to the growing conditions.

Not enough data are available at present to establish a corresponding general curve for fertilized stands.

The regression lines for second harvests (see Table C-XV) are also plotted on Figure C-XXIII. There are significant differences between species which will be discussed later. Following the same procedure as in the case of first harvests, a "general unfertilized" line has been generated on the basis of the data points for hybrid poplar, black cottonwood and unfertilized sycamore. In the case of sycamore, the data points for the Skull Shoals site were not included, because this site suffers from lack of moisture during part of the growing season, and thus, its growth

TABLE C-XV

ESTIMATES OF THE CONSTANTS γ_1 AND γ_2 IN EQUATION C-26 FOR *SECOND HARVESTS* FROM A VARIETY OF DECIDUOUS SPECIES GROWN AT SEVERAL SITES WITH VARIOUS CULTURAL TREATMENTS

Species	Footnotes	Estimate of γ_1		Estimates of γ_2	
		Mean Value	Standard Deviation	Mean Value	Standard Deviation
Black Cottonwood	1	1.73073	0.44386	1.03655	0.14177
Hybrid Poplar NE-388	2	0.83722	0.16777	1.21622	0.22247
Sycamore-fertilized:					
-stumps 1 year old	3	1.28845	0.17049	0.49293	0.05383
-stumps 1 year old	4	3.41624	1.55537	0.48972	0.17986
-all one-year-old stumps	5	2.09800	1.67990	0.49133	0.29913
-stumps 2 years old	6	0.77471	0.10153	1.16185	0.06064
-all stumps	7	1.93316	1.22055	0.57486	0.25085
Sycamore-unfertilized					
-stumps 1 year old	8	0.34143	?	1.13752	?
-stumps 1 year old	9	0.49609	0.17256	1.21388	0.14617
-all 1-year-old stumps	10	0.54467	0.32871	1.07812	0.23051
Black Cottonwood, Hybrid Poplar & Sycamore-Unfertilized	11	1.09849	0.27967	1.01450	0.14192

Footnotes	Source	Site	Reference
1	Table C-VII	Mt. Vernon, Wash.	19
2	"	Musser Farm, Pa.	1
3	"	Georgia Piedmont Bottomland	23
4	"	Georgia Piedmont Bottomland	23
5	"	See footnotes 3 & 4	21 & 23
6	"	Georgia Piedmont Bottomland	29
7	"	See footnotes 5 & 6	21, 23 & 29
8	"	Georgia - Skull Shoals	26
9	"	Georgia - Falling Creek	26
10	"	See footnotes 8 & 9	26
11	"	Georgia, Pennsylvania & Wash.	1, 19, 26 & 32

potential is not in line with the other sites considered[26]. The data points and resulting regression line are plotted on Figure C-XXVII. An individual point for red alder (0.4 square feet per plant - Table C-VII) is also shown. Although this point corresponds to a planting area well out of the range of planting areas for the other data, it is not too far from the general line.

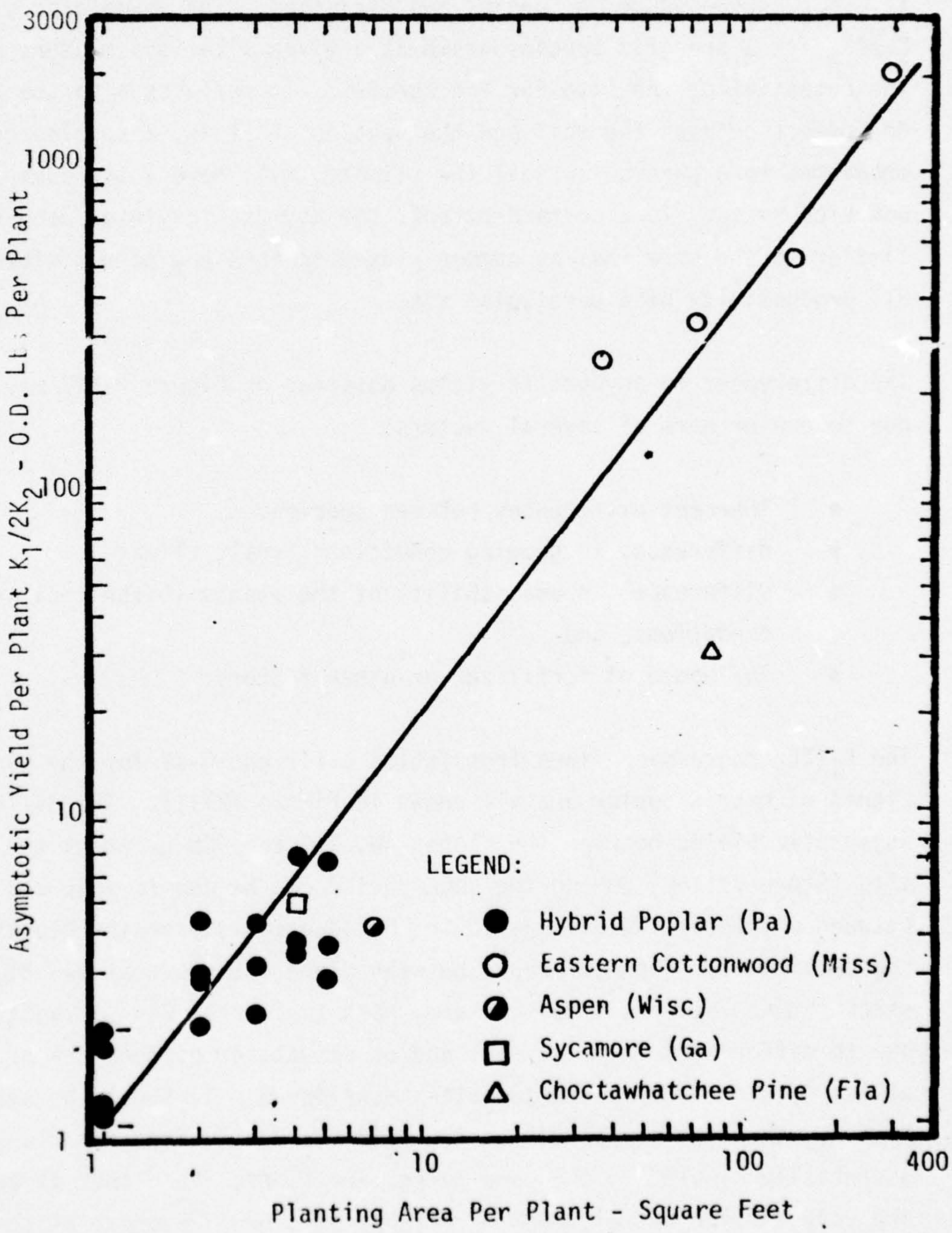
Thus, as is the case for first growth, it is suggested that in the case of species for which a $K_1/2K_2$-versus-A correlation is not available for second harvests under unfertilized conditions, the "general unfertilized" relation in Figure C-XXVII be used provided the growing conditions are good and the species is well adapted to these conditions.

The preceding discussion indicates that:

- within the limits of uncertainty mentioned, the linear dependence of $K_1/2K_2$ on A on a log-log plot appears well established for first and second harvests at planting areas per plant of interest for Energy Plantations;
- the slope of the $K_1/2K_2$-versus-A relationship for first harvests varies widely between species, and because of the large uncertainty in the values for γ_1 and γ_2, it is impossible to make any generalizations;
- the slopes of the $K_1/2K_2$-versus-A relationship for second harvests for unfertilized stands are very similar for the species considered, while the slope for the only fertilized case is significantly different;
- for first and second harvests under unfertilized conditions, general $K_1/2K_2$ lines applicable to a wide variety of species may be defined; and
- for a given planting density, the absolute value of $K_1/2K_2$ for first and second harvests depends on the species.

FIGURE C-XXVI

REGRESSION LINE FOR *FIRST HARVESTS* CALCULATED USING EQUATION C-26 AND THE γ VALUES FOR UNFERTILIZED COTTONWOOD AND HYBRID POPLAR FROM TABLE C-XIV, FOOTNOTE 10



IV.B.8.b. <u>Dependence on Species and Varieties</u>. The asymptotic yield $K_1/2K_2$ for a specific species grown at a given site is a measure of the potential of the site for the species. It reflects also the interdependence between the soil and the species; that is, a species completely unadapted to a particular soil (or climate) will have a low asymptotic yield, and vice versa. To a certain extent, the asymptotic yields used here are similar to the site indices commonly used in forestry to describe the overall productivity of a particular site.

The differences in asymptotic yields observed on Figure C-XXV may be due to one or more of several factors:

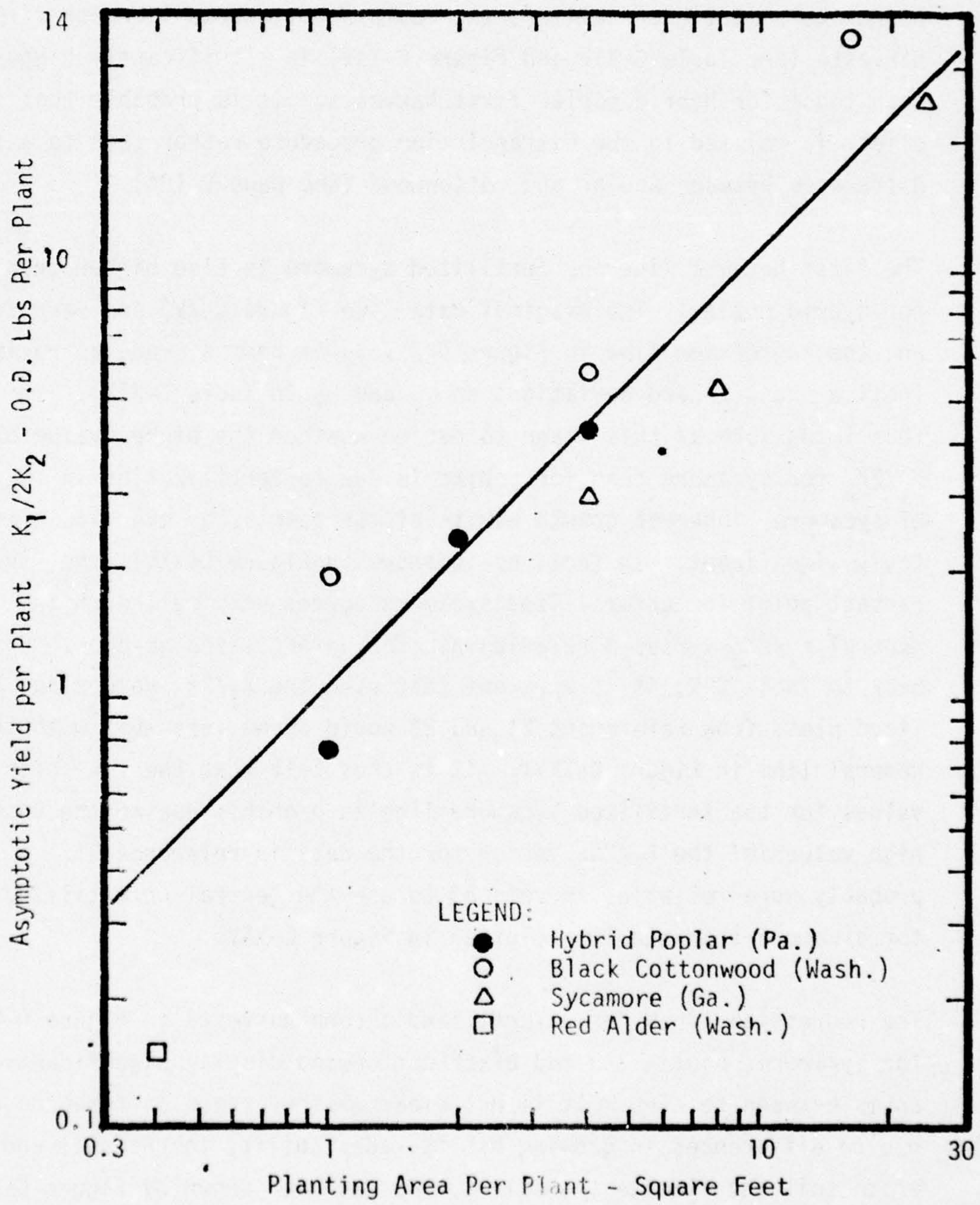
- inherent differences between species,
- differences in growing conditions (soil, climate),
- differences in adaptability of the plants to the local growing conditions, and
- influence of fertilizer or other factors.

The $K_1/2K_2$ regression lines from Tables C-XIV and C-XV for the various clones of hybrid poplar are all shown in Figure XXVIII. The differences in asymptotic yields between the clones 49, 252 and 388 grown at the same site (Stone Valley) during the same period can be due to inherent differences between clones or the difference in the adaptability of the clones to the local growing conditions. The difference between clone 388 grown at two different sites (Stone Valley and Musser Farm, both in Central Pennsylvania) could be due to differences in local soil and/or climate or differences of adaptability of clone 388 to the two sites considered. It should be stressed, however, that the slopes of the two $K_1 2K_2$-versus-A lines for clone 388 are essentially equal. By the same token, the slopes for clones 49 and 252 are very similar but different from that of clone 388 grown at the same location.

FIGURE C-XXVII

REGRESSION LINE FOR *SECOND HARVESTS* USING EQUATION C-26

AND THE γ VALUES SHOWN IN FIGURE C-XV, FOOTNOTE 11



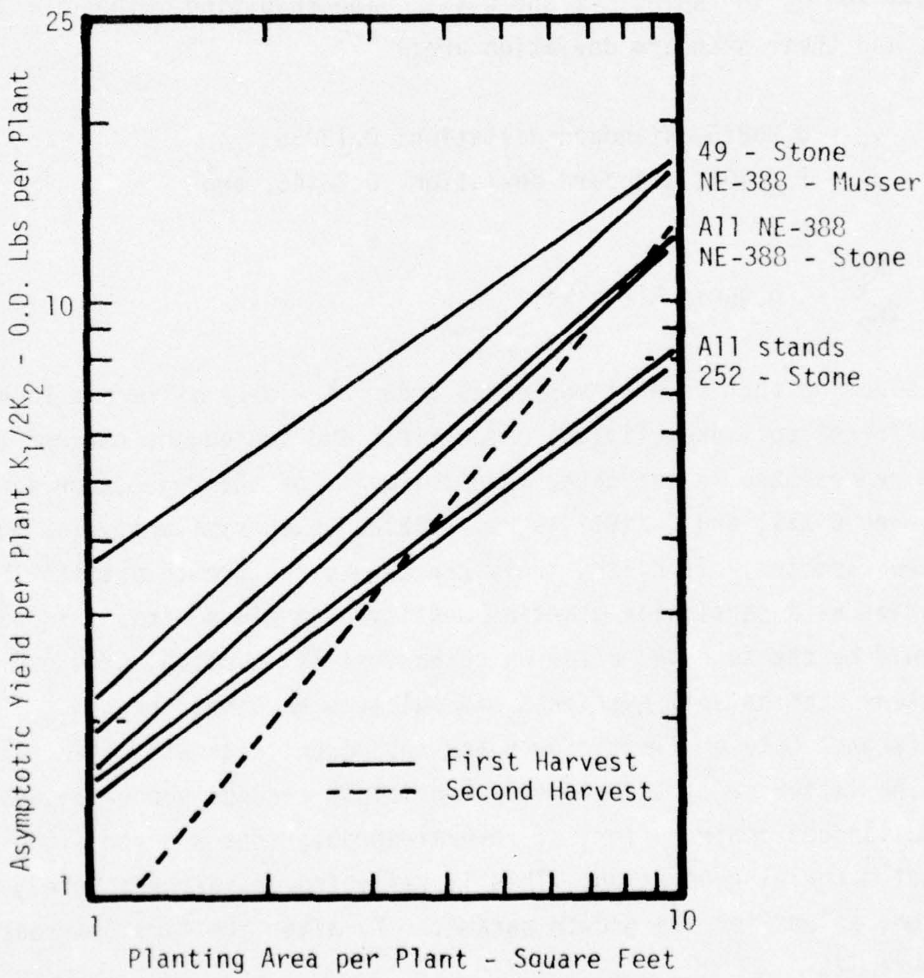
As has been mentioned earlier, the eastern cottonwood line for first harvests (see Table C-XIV and Figure C-XXV) is significantly higher than those for hybrid poplar first harvests. It is probable that this effect is related to the extrapolation procedure rather than to a true difference between poplar and cottonwood (see page C-104).

The first harvest line for fertilized sycamore is also higher than those for hybrid poplar. The original data (see Figure C-XV) are very scattered, and the regression line in Figure C-XXV is at best a crude approximation (notice the standard deviations on γ_1 and γ_2 in Table C-XIV). It is thus impossible at this stage to decide whether the higher value of $K_1/2K_2$ for sycamore than for poplar is due to fertilization in the case of sycamore, inherent growth habits of the species or even if it is truly significant. In fact, as is shown in Figure C-XXVI, the first-harvest point for unfertilized sycamore agrees very well with the general $K_1/2K_2$-versus-A relationship for unfertilized species. Going back to Table C-V, it is apparent that even the $K_1/2K_2$ values for fertilized plots from references 21 and 23 would agree very well with the general line in Figure C-XXVI. It is thus felt that the very high values for the fertilized sycamore line is probably due to the unsually high values of the $K_1/2K_2$ factor for the data in reference 31. It is probably more reliable, therefore, to use the general unfertilized line for sycamore than the line plotted in Figure C-XXVI.

The regression lines for unfertilized second harvests in Figure C-XXV for sycamore, poplar 388 and black cottonwood display significant differences between species. It is not clear whether these differences are due to differences in growing habits, adaptability to the soil and climate or to soil and climate themselves. As has been shown by Figure C-XXVII, the available second-harvest data may be represented by a "general unfertilized" line with a good approximation.

FIGURE C-XXVIII

ESTIMATED VALUES OF THE ASYMPTOTIC YIELD PER PLANT FOR VARIOUS HYBRID POPLAR STANDS IN PENNSYLVANIA



It is apparent from Tables C-XIV and C-XV that the "general unfertilized" lines for first and second harvests have very similar intersections at the origin, γ_1 and similar slopes. A regression analysis has been made for all the data from first and second harvests taken from unfertilized sites--that is the data in references 1, 10, 17, 19, 26 (Falling Creek only) and 32 in Tables C-V and C-VII. The resulting values for the γ's and their standard deviation are:

γ_1 = 0.95815, standard deviation: 0.13036,

γ_2 = 1.26494, standard deviation: 0.06446, and

$$\frac{K_1}{2K_2} = 0.95815 . A^{1.26494} \qquad \text{(C-27)}$$

Considering that several varieties grown at widely different locations (different soil and climate) under first and subsequent harvest conditions are represented in the data, the similarity of the regression lines in Figures C-XXVI and C-XXVII is remarkable. Such similarity is, however, to be expected. If $K_1/2K_2$ truly represents the growth potential of a species at a particular planting density on a given site, this potential should be the same no matter which harvest is involved, provided conditions such as soil nutrients and moisture have not changed. The essential difference between first growth and subsequent regrowth after harvests is that in the latter case, the growth potential is reached sooner because of the simultaneous contributions of several sprouts from a given stump to plant material generation. This is reflected, as already noted, by larger values for the growth parameter K_1 after the first harvest than before it.

The data for first and second harvests from hybrid poplar NE-388 (see Figures C-XXV and C-XXVIII), however, do not seem to support the reasoning in the preceding paragraph. The line for second harvests crosses the line for first harvests at a value for A between about eight and nine square feet per plant, the line for second harvests being below that for first harvests for values A less than about eight square feet. The reason for this behavior is not clear. It may, however, be due to the fact that many of the first harvests in the data were taken when the plants were only a year old, that is before their root structure had developed to the point where it could sustain fully the vigorous regrowth characteristic for second and subsequent harvests. This possibility is supported by the fact that as planting density decreased (higher values for A), the value for $K_1/2K_2$ gained and finally overtook the corresponding value for first harvests. If this analysis is actually correct, it would be expected that $K_1/2K_2$ after the second harvest would conform to the reasoning in the preceding paragraph. Experimental data are not available for checking this point.

Two approaches are suggested for cases similar to those just discussed for certain hybrid poplars. The first is to use the $K_1/2K_2$ versus A relationship calculated from the first harvest data. The second is to use a regression line calculated from the data for first and second harvests, which in the case of the hybrid poplar NE-388 data in references 1 and 17 would be:

γ_1 = 1.32574, standard deviation: 0.40203,

γ_2 = 1.06119, standard deviation: 0.33389,

and

$$\frac{K_1}{2K_2} = 1.32574\ A^{1.06119} \tag{C-28}$$

The data for the fertilized sycamore--see Figure C-XXV--do not seem to support completely the idea of a single $K_1/2K_2$-versus-A relationship for first and second harvests. The regression lines for various fertilized sycamore plantings calculated from the estimates shown in Table C-XV are plotted in Figure C-XXIX. The two isolated points are values of $K_1/2K_2$ for first harvests shown in Table C-V. The point A is from the same stand as the regression line F for second harvests, and the point E is from the stand for which the second-harvest regression line is line C. While the agreement between first and second harvest data is very good in the case of point E and line C, there appears to be no correlation between the corresponding data in the case of point A and line F. No data for first harvests are available, unfortunately, for line B. The argument about the equivalence of the growth potential $K_1/2K_2$ for first and subsequent harvests advanced in the case of unfertilized experiments should be equally valid, and more so, in the case of fertilized experiments. In the latter case, use of fertilizers between successive harvests should maintain the growth potential of a site at the same level irrespective of the number of harvests taken. For lack of further data, it will be accepted that under fertilized conditions, the asymptotic yields $K_1/2K_2$ for first and subsequent harvests are equal. This assumption is also supported by the evidence concerning the influence of fertilizer (section IV.3.6.d.) which indicates that fertilization brings the growth potential of sites having various site indices up to the equivalent of an index of 100 or better.

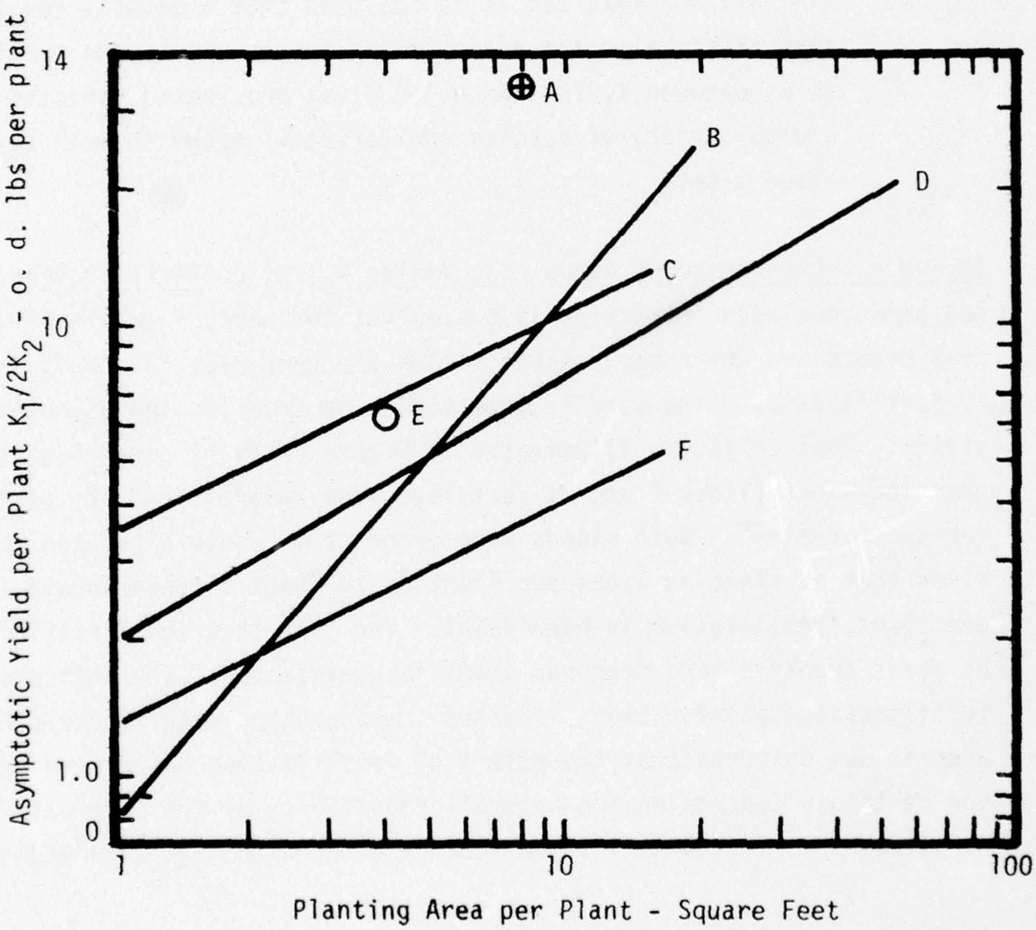
The differences between the line B and the lines C and F and the overall average (line D) are significant but unexplained.

The discussion of the dependence of the asymptotic yield per plant $K_1/2K_2$ on species and varieties indicates that:

- there appear to be differences in the $K_1/2K_2$ versus A relationships between species and varieties;
- the same $K_1/2K_2$-versus-A relationship appears to apply for the first and subsequent harvests from a particular species or variety at a given site and cultural treatment program--for unfertilized sites, and despite the variation in the $K_1/2K_2$-versus-

FIGURE C-XXIX

ESTIMATED VALUES OF THE ASYMPTOTIC YIELD PER PLANT FOR VARIOUS FERTILIZED SYCAMORE STANDS



LEGEND:

A = Value of $K_1/2K_2$ for a first harvest, Figure C-V, reference 23.

B = Regression line calculated from second harvest, γ estimates in Table C-XV, footnote 6.

C = Regression line calculated from second harvest, γ estimates in Table C-XV, footnote 4 (reference 21)--compare with E.

D = Regression line calculated from second harvest, γ estimates for all stumps in Table C-XV, footnote 7.

E = Value of $K_1/2K_2$ for a first harvest, Figure C-V, reference 21.

F = Regression line calculated from second harvest, γ estimates in Table C-XV, footnote 3 (reference 23)--compare with A.

A relationship between species, the relationships for a wide variety of species are fairly closely represented by a single general relationship which approximate the specific relationships for individual species and varieties (Figure C-XXVI);

- the data suggest, and it is accepted that a general relationship exists also for representing approximately the relationships between $K_1/2K_2$ and A for first and second harvests from a wide variety of species and varieties grown in well fertilized sites.

IV.B.8.c. Dependence of Asymptotic Yields $K_1/2K_2$ on Fertilization. It has been concluded in section IV.B.6.d. that the rate of growth of individual plants and their harvestable yields are generally favorably influenced by fertilization. The same is expected to be true for the asymptotic yields. That it is, is illustrated in Figure C-XXV by comparing the regression lines (lines F and H, fertilized and unfertilized, respectively) for sycamore[21,26]. Both stands were grown at the same site, and it is clear that at planting areas per plant up to about fifteen square feet per plant, fertilization is beneficial. The fact that the lines intersect at about twenty square feet per plant is unexplained. The influence of fertilization has also been discussed in connection with Figure C-XXIII when it was observed that the effect of fertilization may depend on species and certainly depends on the natural productivity of the site--use of fertilizer has less beneficial effect on sites with high site indices.

It can be concluded that fertilization will increase the asymptotic yield per plant $K_1/2K_2$, but the level of improvement is related to species, site index, and eventually in the last analysis to such other factors as the moisture supply during the growing season.

IV.B.9. Dependence of Yield on Climate and Other Factors.

IV.B.9.a. Introduction. Although quite a number of measurements of yields from fast-growing deciduous tree species planted at high densities and harvested on short cycles have been made in the United States, no data along these lines appear to have been generated in the locale of Fort Leonard Wood. Data for sycamore have been collected at sites in Georgia about one hundred miles to the northeast and south of Fort Benning, but few data for other species of greater interest for Energy Plantations seem to have been collected in the "greater" Fort Benning region. There is need, therefore, for extrapolating or "handicapping" yield data for a given species from the locality where the measurements were made to sites of interest, such as Forts Benning, Leonard Wood and elsewhere.

The harvestable yield from a given species at a particular site depends on a number of factors which can be grouped into two general categories:

- those factors which can be controlled or modified at reasonable cost, and
- those which are either physically uncontrollable or cannot be controlled or modified at reasonable cost.

Among the controllable factors is the choice of species. The plantation designer is free to choose from among a number of deciduous species those which can reasonably be expected to survive and grow well in the soil and climate at the site of interest. The availability of nutrients and the soil pH at the site can often be controlled at tolerable cost, although to do so may be uneconomical for some sites.

Among the uncontrollable factors are the climate itself and particularly:

- the duration of the frost-free period each year,
- the profile and absolute levels of ambient temperatures, and
- insolation and regularity of soaking rains during the growing season.

Other factors uncontrollable on a scale commensurate with the needs of Energy Plantations are the nature of the soil and its texture (sandiness, rockiness and clay components) at the surface and a few feet down. The amount of moisture held in the soil is another relatively uncontrollable factor. Predicting the effect of these and other uncontrollable factors on the harvestable yield from fast-growing deciduous species is the purpose of the immediately ensuing analysis.

<u>IV.B.9.b. Climate-Yield Relationships</u>. An expression relating the amount of harvestable plant material generated during a growing season to fundamental parameters such as the rate of photosynthesis, the duration of the growing season and the insolation rate and temperature profile during the growing season is developed in this section. The validity of the expression will be tested in the next following section.

Various models have been proposed for predicting growth rates[39,40,41,42,43]. The present analysis draws on aspects of these.

The basic equation used for estimating the yield of plant material above the ground y_t at time t is

$$y_t = y_{t-1} + k\ (t)\ P\ (t) \tag{C-29}$$

where

y_t = the plant material above the ground, pounds per plant at time t,

$P(t)$ = the total amount of photosynthesized material per plant during the time interval $(t-1)$ to t.

$k(t)$ = the fraction of the photosynthetized material contributing to the accumulation of plant material above ground per plant.

Equations similar to C-29 may be written for other parts of the plant such as its roots and leaves.

To obtain the yield accumulation during a growing season, equation C-29 must be integrated over time for the whole season. In the first approximation considered here, the integration will be done stepwise for one-month periods, using average monthly climate data for each month in the growing season.

The amount of plant material generated by photosynthesis during a one-month period, $P(t)$, may be expressed as

$$P(t) = R\,L_e \tag{C-30}$$

where R = the rate of photosynthesis, milligrams of carbon dioxide assimilated per month per unit surface of effective leaf area,

L_e = the effective leaf area per plant, square decimeters,

$L_e = \varepsilon L$,

L = total leaf area per plant, and

ε = the fraction of the total leaf area which received enough light to contribute significantly to the photosynthesis process.

The total leaf area per plant L may be expressed as a function of the total dry weight of plant material above ground, that is the stem and branches but excluding the leaves, through:

$$L = \gamma\, y \tag{C-31}$$

A correlation such as C-31 between leaf area and the dry weight of plant material (excluding the leaves) per plant above ground has been found to hold for several hybrid poplars[40,44].

Equations C-30 and C-31 lead to:

$$\begin{aligned} P(t) &= RL_e = R\varepsilon L = \varepsilon\gamma R y_{t-1} \\ &= \alpha R y_{t-1} \end{aligned} \tag{C-32}$$

where α equals $\varepsilon\gamma$. Equation C-32 indicates that the amount of plant material generated photosynthetically during a given period is proportional to the amount of dry plant material present at the end of the previous period.

Thus, from equations C-29 and C-32, the yield y_i at the end of the i^{th} month of a growing season is

$$y_i = y_{i-1} + \alpha k R_i y_{i-1} = (1 + \alpha k R_i)\, y_{i-1} \tag{C-33}$$

where R_i is the rate of photosynthesis during the i^{th} month of the growing season.

It can readily be seen from equation C-33, that the cumulated yield y at the end of a growing season comprising n monthly periods is

$$y = (1 + \alpha kRn)\,(1 + \alpha kR_{n-1})\ldots(1 + \alpha kR_1)y_0 \tag{C-34}$$

where y_0 is the amount of dry plant material above ground at the onset of the growing season.

The photosynthetic rate R_i in a given month may be approximated by

$$R_i = (15.22\ h_i)\left[2 - e^{\frac{-0.05088\ I_i}{h_i}}\right]\theta_i\ d_i\left(\frac{\text{mg } CO_2}{\text{dm}^2\text{- month}}\right) \qquad \text{(C-35)}$$

where h_i = the average number of hours of sunshine per day during the i^{th} month of the growing season,

I_i = the average daily insolation during the i^{th} month, expressed in Langley per day (1 Btu per day per ft^2 = 3.7 Langleys per day = 3.7 Cal per cm^2 per day)--Langleys are used because most insolation data are given in these units (reference 45, for instance),

θ_i = a temperature weight - factor equal to $1 - 0.0016\ (T - 65)^2$-- this factor is a parabolic function of temperature having a maximum value of one at 65° Fahrenheit, and zero at 40° and 90° Fahrenheit, respectively. The factor θ takes into account the fact that, all other conditions being the same, the rate of photosynthesis for most deciduous species increases from about zero at 40° Fahrenheit to a maximum at about 65° Fahrenheit, and then decreases as the temperature increases further to about zero at about 90° Fahrenheit. This behavior is a general characteristic of C_3 plants which "shut-off" their synthesis mechanism as the temperature reaches about 90° Fahrenheit[5],

d_i = the number of days during which photosynthesis is expected to occur in a month in the growing season. In spring, the last date of frost is taken as the start of the growing season. The number of growing days during that first month is thus taken to be the number of days between the last frost and the end of the month. The same principle, but reversed, is applied to the last month of the growing season. Also, days with temperatures above 90°F are discounted as little or no photosynthesis is expected to occur under these conditions. Thus,

d_i = (number of days in month i) - (number of days with $T < 32°F$) - (number of days with $T > 90°F$)

Expression C-35 is valid[40] for the Populus clone W-5. Similar reations can be established for other varieties.

The effective leaf area L_e is given by

$$L_e = \varepsilon L = \varepsilon\gamma y \tag{C-36}$$

where γ = 0.41 dm^2 per g of dry plant material, excluding leaves, above ground--this value for γ was determined for aspen suckers in Minnesota[46].

ε = fraction of leaves effective in the photosynthesis process; two values are adopted--ε equals one for one and two-year-old plants for which probably all the leaves are active, and 0.2 for three and four-year-old plants for which the canopy is closed and the "inside" leaves receive very little useful light, thus reducing their effectiveness for photosynthesis to almost nothing.

Thus

$$L_e = 0.41\ y\ dm^2 \text{ for one and two-year-old plants, and} \tag{C-37}$$
$$L_e = 0.082\ y\ dm^2 \text{ for three and four-year-old plants} \tag{C-38}$$

The fraction k of photosynthetically produced material contributing to the plant material above the ground (stem and branches, but not leaves) depends on the species considered. The value

$$k = 0.5 \tag{C-39}$$

has been adopted on the basis of data for various clones of hybrid poplar grown in Pennsylvania[17].

Thus, on the basis of equations C-30, C-33, C-35 and C-39:

$$y_i = y_{i-1} \left\{ 1 + \begin{pmatrix} 0.41 \\ \text{or} \\ 0.082 \end{pmatrix} 0.5\text{x}10^{-3} \left(15.22h_i\right) \left[1 - e^{\frac{-0.05008I_i}{h_i}}\right] \theta_i d_i \right\} \quad \text{(C-40)}$$

or

$$y_i = y_{i-1} \left(1 + 2.05\text{x}10^{-4} \text{ x } R_i\right) \text{ for plants one and two years old} \quad \text{(C-41)}$$

and

$$y_i = y_{i-1} \left(1 + 4.1\text{x}10^{-5} \text{ x } R_i\right) \text{ for plants three and four years old} \quad \text{(C-42)}$$

IV.B.9.c Test of The Climate-Yield Relationship. To establish that the climate-yield relations C-41 and C-42 are useful and reliable tools for predicting yields at a given site on the basis of data generated at other sites, the relations must be tested at two levels. First, the relations must adequately predict the growth of a given species during a growing season at a given site. Second, they must predict the ratio of the yields of a given species grown at two different sites.

Yield at a Given Site. A site in central Pennsylvania near State College for which a significant amount of data is available for several hybrid poplars[1,17] has been chosen for partially testing relations C-41 and C-42. Yields were estimated from equations C-41 and C-42 following the steps defined in equations C-29 and C-34. The results, given in Table C-XVI, are expressed as ratios of the amount of dry plant-material above the ground per plant y_n at the end of the season to the amount at the beginning of the season, and are, therefore, a measure of the increase in plant material per plant per year.

The calculated yield ratios from Table C-XVI are compared in Table C-XVII with those from actual data for hybrid poplars NE-388 and 49 grown in central Pennsylvania[1,17]. The estimated yield ratios shown in the right-hand column of Table C-XVII were chosen from the two ratios estimated in Table C-XVI according to the following considerations:

- equations C-41 and C-42 do not take explicit account of planting density; therefore,
- for first harvests taken in the second growing season or earlier, yield ratios based on equation C-41 have been selected,
- for first harvests taken after the end of the second growing season, yield ratios based on equation C-41 have been used,
- for all second harvests irrespective of the number of seasons since the first harvests, yield ratios based on equation C-41 have been used.

The reasonableness of this procedure for choosing which equation to use is borne out by comparison of the actual and estimated yield ratios shown in Table C-XVII.

Examination of the actual and estimated yield ratios in Table C-XVII reveals that:

- actual yield ratios prior to the first harvest are usually much larger for two-year-old plants than for three-year-old or older plants--a finding which supports the idea of different effective leaf areas as a function of plant age--the difference in effective leaf area assumed is reflected in the difference between equations C-41 (two-year-old or young plants) and C-42 (three-year-old or older plants);

- actual yield ratios for two-year-old plants prior to the first harvest generally increase sharply with increasing planting area per plant--a finding supporting the conclusion that, as planting density increases, interference between plants because of mutual shading from the sun becomes an increasingly significant limitation on the growth rate;
- as the age of the plant prior to first harvest increases, the actual yield ratios decline, but the ratio at a particular age over two is almost independent of planting density and whether the plants are from clone NE-388 or clone 49--this regularity of behavior may reflect the paramount importance of shading between adjacent plants as a limiting factor on the rate of growth per plant;
- as the age of the plant material increases after the first harvest, the actual yield ratios tend to decline, but the pattern is not as clear-cut as it is for growth prior to the first harvest;
- the averages of actual yield ratios at a given planting density between the begining and end of a single growing season for the third through the fifth growing season (through the fourth in the case of poplars from clone 49) are very close to the ratios estimated from equation C-42; and
- the averages of all the actual yield ratios at a given planting density between the beginning and end of a single growing season are very close to, but in every instance slightly below, the ratios estimated from equation C-42.

These observations based on the comparison between actual and estimated yield ratios shown in Table C-XVII suggest that, in the absence of some major growth-limiting factor such as a restricted moisture supply, yield estimations based on insolation rates, ambient temperatures, the duration

TABLE C-XVI

ESTIMATED RATIOS BASED ON EQUATIONS C-41 AND C-42 OF PLANT MATERIAL ABOVE GROUND AT END AND BEGINNING OF GROWING SEASON AT STATE COLLEGE, PENNSYLVANIA

Month	Factors and Notes									
	T_i	θ_i	h_i	days > 90°F	d_i	I_i	r_i	R_i	y_t/y_{t-1}	y_t/y_{t-1}
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
April	49.0	0.59	7.67	-	0	380	-	-	-	-
May	59.5	0.95	8.93	1	25	456	125.8	2988	1.61	1.12
June	68.1	0.98	9.90	5	25	518	140.2	3435	1.70	1.14
July	71.9	0.92	10.29	9	22	511	144.1	2917	1.60	1.12
August	69.9	0.96	9.10	7	24	444	126.9	2924	1.60	1.12
September	62.8	0.99	7.77	2	28	358	106.9	2963	1.61	1.12
October	52.7	0.76	6.45	-	10	256	85.1	647	1.13	1.03
y_n/y_o (note 11):										
For one and two-year-old plants									12.75	
For three and four-year-old plants										1.85

TABLE C-XVI (continued)

ESTIMATED RATIOS BASED ON EQUATIONS C-41 AND C-42 OF PLANT MATERIAL ABOVE GROUND AT END AND BEGINNING OF GROWING SEASON AT STATE COLLEGE, PENNSYLVANIA

NOTES

(1) Average monthly temperature (°F) from Monthly Normals of Temperature, Precipitation and Heating and Cooling Degree-Days, 1941-1970, U.S. Dept. of Commerce[47].

(2) $\theta_i = 1-0.0016\ (T_i-65)^2$

(3) Average number of hours of insolation per day from Climatic Atlas of the United States[45].

(4) Average number of days with T over 90° Fahrenheit from Climatic Atlas of the United States[45].

(5) Effective growing days during i^{th} month--dates of last and first frosts are from reference 45.

(6) Average daily insolation (Langleys per day) from Climatic Atlas of the United States[45].

(7) Average daily rate of photosynthesis, $r_i = 15.22\ h_i \left[1-e^{\frac{-0.05088 I_i}{h_i}}\right]$, during i^{th} month--milligrams of carbon dioxide per square decimeter of leaf area per day.

(8) Average monthly rate of photosynthesis, $R_i = r_i x \theta_i x d_i$--milligrams of carbon dioxide per decimeter of leaf area per month.

(9) Fractional increase in plant material above ground during the month--$y_i/y_{i-1} = 1+2.05x10^{-4}\ P_i$, for one and two-year-old plants (equation C-41).

(10) Fractional increase in plant material above ground during the month--$y_i/y_{i-1} = 1+4.1x10^{-5}\ P_i$, for three and four-year-old plants (equation C-42).

(11) Ratio of plant material above ground at end and beginning of the growing season--$y_n/y_o = (1+\alpha kR_n)\ (1+\alpha kR_{n-1})\ldots(1+\alpha kR_i)$--equation C-34.

of the frost-free period, and hours of sunshine per day, as accounted for in equations C-41 and C-42 are a reliable indication of the plant-material production potential from first and second harvests at a particular site.

The information in Table C-XVII and the accompanying discussion are limited to two hybrid poplars in Pennsylvania. Similar estimates made for other species in other locations, namely aspen in Minnesota and Wisconsin and cottonwood in Mississippi and Kansas (limited data in the latter case) show that the conclusions reached from Table C-XVII are valid for the other species-location combinations.

Relative Yields Between Sites. Comparisons between the growth potential of two different sites have also been made on the basis of equations C-41 and C-42. Strictly speaking, these comparisons should have been made for the same species or variety at two locations. Unfortunately, sufficient data for this purpose for a given species grown at two different locations are not available. The comparisons have been made, therefore, for similar, or thought-to-be similar, species grown at different locations. These species and locations are hybrid poplars in central Pennsylvania, eastern cottonwood in Mississippi, Missouri and Sioux cottonwood in Kansas and aspen in Wisconsin. The limited data available with respect to the values for parameters in equations C-41 and C-42, such as the rate of photosynthesis and the leaf-area-to-plant-weight ratio (see references 40, 41, 42 and 46), suggest that these values should not differ very much between species. Estimations of the yield ratios y_n/y_{n-1} analogous to those described in Table C-XVI have been made for the species and locations mentioned earlier in this paragraph. The results of these calculations are compared with actual data in Table C-XVIII.

TABLE C-XVII

COMPARISON OF CALCULATED YIELD RATIOS OVER ONE SEASON TABLE C-XVI WITH ACTUAL RATIOS FOR HYBRID POPLAR NE-388 AND 49 GROWN IN CENTRAL PENNSYLVANIA

Species	Planting Density Ft^2/Plant	Harvest	Growing Season*	Actual Yield Ratio: For one Season	Actual Yield Ratio: Average of Seasons	Estimated Yield Ratio
Hybrid poplar NE-388	1	1st	2nd	5.54		12.75
	1	"	3rd	2.53	1.81	1.85
	1	"	4th	1.62		1.85
	1	"	5th	1.27		1.85
	2	"	2nd	7.43		12.75
	2	"	3rd	2.60	1.86	1.85
	2	"	4th	1.56		1.85
	2	"	5th	1.42		1.85
	4	"	2nd	2.11		12.75
	4	"	3rd	2.75	1.90	1.85
	4	"	4th	1.57		1.85
	4	"	5th	1.38		1.85
	1	2nd	2nd	1.95	1.79	1.85
	1	"	3rd	2.39		1.85
	1	"	4th	1.02		1.85
	2	"	2nd	2.00	1.56	1.85
	2	"	3rd	1.64		1.85
	2	"	4th	1.03		1.85
	4	"	2nd	2.03	1.75	1.85
	4	"	3rd	2.15		1.85
	4	"	4th	1.08		1.85
Hybrid poplar 49	1	1st	2nd	9.10		12.75
	1	"	3rd	2.05	1.74	1.85
	1	"	4th	1.44		1.85
	2	"	2nd	12.67		12.75
	2	"	3rd	2.29	1.90	1.85
	2	"	4th	1.51		1.85
	3	"	2nd	14.75		12.75
	3	"	3rd	2.55	2.04	1.85
	3	"	4th	1.53		1.85
	4	"	2nd	14.66		12.75
	4	"	3rd	2.80	2.18	1.85
	4	"	4th	1.56		1.85
	5	"	2nd	19.47		12.75
	5	"	3rd	2.77	2.15	1.85
	5	"	4th	1.53		1.85

* In the case of second harvests, seasons are counted from the year of the first harvest

Comments are appropriate about the comparison between the experimental and estimated ratios shown, respectively, in the fifth and sixth columns in Table C-XVIII. In every case, hybrid poplar grown at Musser Farm in central Pennsylvania from clone NE-388 was used as the basis for comparison. A ratio larger than one in column five or six indicates the growth potential as determined by the climate factors used in equations C-41 and C-42 is larger at the Pennsylvania site than at the second site in the comparison. By this standard, the growth potentials at the Pennsylvania and Mississippi sites are about equal.

In the comparison between the Pennsylvania and Wisconsin sites, the estimated ratios are of the right magnitude, except for that based on the fourth growing season. The discrepancy in this latter case may be due to the fact that the actual Pennsylvania planting was at four square feet per plant, whereas, the Wisconsin planting was at seven. As previously noted, at higher planting densities, interference between plants develops sooner as the factor limiting growth rate than it does at lower planting densities. Therefore, the experimental ratio between the two sites for the fourth season may be unrealistically low. However, the average of the experimental ratios for the third and fourth growing seasons is 1.07, which is very close to the estimated ratio--namely, 1.11.

It can be concluded, therefore, that the Pennsylvania and Wisconsin sites are practically equivalent to one another in terms of the effect on growth potential of the climatic factors accounted for in equations C-41 and C-42. It cannot be concluded, however, that the harvestable yields from aspen and the hybrid poplar at their respective sites after a given number of growing seasons will be equal. To compare the absolute yields between the species at their respective sites, it would be necessary to know the photosynthetic efficiencies and other growth characteristics involved in equations C-41 and C-42 for each of the two species. This information is

TABLE C-XVII

COMPARISON OF CALCULATED YIELD RATIOS OVER ONE SEASON
TABLE C-XVI WITH ACTUAL RATIOS FOR HYBRID POPLAR
NE-388 AND 49 GROWN IN CENTRAL PENNSYLVANIA

Species	Planting Density Ft^2/Plant	Harvest	Growing Season*	Actual Yield Ratio: For one Season	Actual Yield Ratio: Average of Seasons	Estimated Yield Ratio
Hybrid poplar NE-388	1	1st	2nd	5.54		12.75
	1	"	3rd	2.53		1.85
	1	"	4th	1.62	1.81	1.85
	1	"	5th	1.27		1.85
	2	"	2nd	7.43		12.75
	2	"	3rd	2.60		1.85
	2	"	4th	1.56	1.86	1.85
	2	"	5th	1.42		1.85
	4	"	2nd	2.11		12.75
	4	"	3rd	2.75		1.85
	4	"	4th	1.57	1.90	1.85
	4	"	5th	1.38		1.85
	1	2nd	2nd	1.95		1.85
	1	"	3rd	2.39	1.79	1.85
	1	"	4th	1.02		1.85
	2	"	2nd	2.00		1.85
	2	"	3rd	1.64	1.56	1.85
	2	"	4th	1.03		1.85
	4	"	2nd	2.03		1.85
	4	"	3rd	2.15	1.75	1.85
	4	"	4th	1.08		1.85
Hybrid poplar 49	1	1st	2nd	9.10		12.75
	1	"	3rd	2.05	1.74	1.85
	1	"	4th	1.44		1.85
	2	"	2nd	12.67		12.75
	2	"	3rd	2.29	1.90	1.85
	2	"	4th	1.51		1.85
	3	"	2nd	14.75		12.75
	3	"	3rd	2.55	2.04	1.85
	3	"	4th	1.53		1.85
	4	"	2nd	14.66		12.75
	4	"	3rd	2.80	2.18	1.85
	4	"	4th	1.56		1.85
	5	"	2nd	19.47		12.75
	5	"	3rd	2.77	2.15	1.85
	5	"	4th	1.53		1.85

* In the case of second harvests, seasons are counted from the year of the first harvest

Comments are appropriate about the comparison between the experimental and estimated ratios shown, respectively, in the fifth and sixth columns in Table C-XVIII. In every case, hybrid poplar grown at Musser Farm in central Pennsylvania from clone NE-388 was used as the basis for comparison. A ratio larger than one in column five or six indicates the growth potential as determined by the climate factors used in equations C-41 and C-42 is larger at the Pennsylvania site than at the second site in the comparison. By this standard, the growth potentials at the Pennsylvania and Mississippi sites are about equal.

In the comparison between the Pennsylvania and Wisconsin sites, the estimated ratios are of the right magnitude, except for that based on the fourth growing season. The discrepancy in this latter case may be due to the fact that the actual Pennsylvania planting was at four square feet per plant, whereas, the Wisconsin planting was at seven. As previously noted, at higher planting densities, interference between plants develops sooner as the factor limiting growth rate than it does at lower planting densities. Therefore, the experimental ratio between the two sites for the fourth season may be unrealistically low. However, the average of the experimental ratios for the third and fourth growing seasons is 1.07, which is very close to the estimated ratio--namely,1.11.

It can be concluded, therefore, that the Pennsylvania and Wisconsin sites are practically equivalent to one another in terms of the effect on growth potential of the climatic factors accounted for in equations C-41 and C-42. It cannot be concluded, however, that the harvestable yields from aspen and the hybrid poplar at their respective sites after a given number of growing seasons will be equal. To compare the absolute yields between the species at their respective sites, it would be necessary to know the photosynthetic efficiencies and other growth characteristics involved in equations C-41 and C-42 for each of the two species. This information is

TABLE C-XVIII

COMPARISONS OF PLANT MATERIAL GROWTH POTENTIAL AT VARIOUS WIDELY SEPARATED LOCATIONS ON THE BASIS OF EQUATIONS C-41 AND C-42

(First-Harvest Data)

Locations Compared[1]	Species Compared[1]	Planting Density[2] Ft^2 per Plant	Growing Season	Yield Ratios[3]	Yield Ratios
Central Pennsylvania and Wisconsin	Hybrid poplar NE-388 and aspen	4 and 7	2nd	2.29	1.47
			3rd	1.24	1.11
			4th	0.90	1.11
Central Pennsylvania and Mississippi	Hybrid poplar NE-388 and cottonwood	4	2nd	0.99	0.78
			3rd	0.98	0.97
			4th	0.99	0.97
Central Pennsylvania and Kansas	Hybrid poplar NE-388 and cottonwood	4	2nd	2.43	1.20
			3rd	1.37	1.06
			4th	1.00	1.06

Footnotes:

1. Central Pennsylvania is Musser Farm - hybrid poplar NE-388 - reference 1.
   Wisconsin - aspen - reference 4.
   Mississippi - cottonwood (*P. deltoides*) - reference 10.
   Kansas - Tuttle and Milford - Missouri and Sioux cottonwood - reference 4.

2. Where two planting densities are reported, the first refers to hybrid poplar and the second to the comparison species.

3. This is the ratio of the experimentally measured (y_n/y_{n-1}) for poplar at central Pennsylvania to the experimentally measured (y_n/y_{n-1}) for the second species at the second location.

4. This is the ratio of the estimated (y_n/y_{n-1}) for central Pennsylvania to the estimated (y_n/y_{n-1}) for the second location--equation C-41 was used for the second growing season estimates, and equation C-42 was used for the third and fourth season estimates.

not known to be available for aspen and is only very approximately known for the hybrid poplar. In fact, it is likely that the absolute yields from aspen would be much lower than from the poplar, because it is known that aspen grows more slowly than the poplar does in the first few years after planting. What the comparison between the Pennsylvania and Wisconsin sites indicates, however, is that if a species suited to the Wisconsin site having a juvenile growth rate comparable with that of the hybrid poplar were to be planted at the Wisconsin site, it would have the same growing potential and approximately the same harvestable yield there as the hybrid poplar does at the Pennsylvania site. A proviso has to be added to this statement--namely, the conclusion would be true only providing the soil quality and moisture supply would not be more restrictive limitations to aspen growth than are the climate conditions allowed for in equations C-41 and C-42.

The experimental data and estimates are in close agreement for the Pennsylvania and lower Mississippi River Valley sites. It can be concluded that the growth potential of the two locations is about equal for species which have the same inherent growth rates. Approximately the same can be said for the Pennsylvania and Kansas sites.

Conclusion. The validation estimates shown in Tables C-XVII and C-XVIII for equations C-41 and C-42 suggest that the equations are good indications of the potential of a site for an Energy Plantation providing that the climate factors in the equations are more restrictive to plant-matter production than are such other factors as soil quality and soil moisture availability.

IV.B.9.d. Influence of Soil Texture and Available Moisture on Yield. As mentioned earlier, moisture available to plants during the growing season and soil texture are two factors which cannot be adjusted easily on a large scale.

The amount of water required by a plant to generate a given amount of dry plant material varies substantially from plant to plant. For instance, Assman [5] estimates that about 350 pounds of water are required per pound of dry plant material produced by oak. For birch, beech and rye, the corresponding ratios are about 300, 170 and 690 pounds of water per pound of dry plant material.

An estimate of the water requirement for hybrid poplar grown in central Pennsylvania has been made on the basis of plant-matter yield for a year[1] and the normal precipitation data during the growing season. It was estimated that these poplars (clone NE-388) required about 150 to 200 pounds of water per pound of dry plant material produced. At a rate of plant-matter production of eight dry tons per acre per year, this would correspond to a water requirement of about 2 to 2.8 inches per month during the growing season.

The total average rainfall per month is not the whole picture, however. The distribution of rainfall in important. Several gentle rainfalls totalling 2 inches per month will be more beneficial than one downpour. One of the reasons for this is that gentle rainfalls have a better chance of soaking into the ground and being retained as available moisture in the soil than does a downpour which is likely to deliver water at a faster rate than can be absorbed by the soil. Consequently, a larger fraction of the water delivered to the soil surface by a downpour is likely to run off the surface and, therefore, not be absorbed by it than is the case for a more gentle rain.

There is no general way for treating this problem at present. Each case will have to be treated separately by taking into account rainfall distribution during the growing season in relation to the soil moisture absorption and retention characteristics.

IV.B.10. Conclusions. The analysis of yields per plant from deciduous species in plantations leads to the following conclusions.

1. The harvestable yield of plant material per plant can be represented by an equation of the following form:

$$y_n = \frac{K_1}{2K_2} \left(1 - e^{-K_2 n^2}\right) \qquad \text{(C-8)}$$

where y_n = the average harvestable yield of plant material per plant at year n in pounds of dry plant material,

n = the age in years of the harvestable plant material above ground since planting if there has been no harvest from the planting, or the age of the plant material since the immediately preceding harvest,

K_1 = a growth parameter, dry pounds of plant material per plant per year squared, and

K_2 = a growth-limiting parameter, a pure number per year squared.

2. The parameters K_1 and K_2 are functions of a number of factors, including the planting area per plant, species, cultural treatments at the plantations, among others.

3. For a particular species grown at a particular site, given at least two harvested yields at the same planting density, but at different numbers of years since planting or since the previous harvest from the planting, the parameters K_1, K_2 and their combination $K_1/2K_2$ can be estimated from equation C-8.

4. Given values for any two parameters chosen from K_1, K_2 and $K_1/2K_2$, yields at numbers of years since planting or since the preceding harvest for which actual data are not available can be estimated reliably at the planting density for which the values of K_1, K_2 and $K_1/2K_2$ are known from equation C-8.

5. For planting areas per plant up to about fifteen square feet (the upper limit of interest for Energy Plantations), the parameters K_1, K_2 and $K_1/2K_2$ are represented as linear functions of the planting area per plant on a log-log plot--these correlations allow harvestable yields to be estimated for planting densities for which values of K_1, K_2 and $K_1/2K_2$ are not available from actual data and, therefore, remove the planting density limitation in point 4.

6. The relationships between K_1 and K_2 and planting area per plant are species-dependent, but the relationship between $K_1/2K_2$ and planting area per plant seems to be independent of species for a wide variety of species of interest for Energy Plantations.

7. An approximate relationship between total insolation and the ambient temperature profile during the growing season on the one hand and the harvestable yield from plantations on the other has been established--it allows fairly reliable estimates to be made of the harvestable yield from a species at a plantation site for which no actual yield data are available, providing insolation and the temperature profile during the growing season are the factors which most restrict plant growth at the plantation site in question--other factors which at certain sites might be more restrictive are precipitation or soil character.

IV.C. Summary of Correlations Applicable to Deciduous-Species Plantations. The various correlations established from experimental data on the yields from deciduous-species plantations are summarized in Table C-XIX.

The factors which have been found to be important for describing the productivity of a deciduous-species plantation are listed in the first column of the table.

TABLE C-XIX

SUMMARY OF CORRELATIONS APPLICABLE TO DECIDUOUS-SPECIES PLANTATION*

FACTOR	CORRELATION	VARIABLES	COMMENTS	ERROR RANGE PERCENT
Number of surviving plants at age n, N_n - plants/acre	$N_n = N_o\ 10^{-an}$	a : A	Depends also on site, climate and cultural treatment	±10 or less
Decay parameter, a - $year^{-1}$	$a = \alpha\ A^{\beta}$	α and β: species		
Harvestable yield per living plant at year n, oven-dry lb/plant at year n	$y_n = \frac{K_1}{2K_2}(1-e^{-K_2 n^2})$	K_1 and K_2: A	K_1 and K_2 also depend on species, climate, management and cultural treatments.	±10 or less
Growth parameter, K_1 - *oven-dry lb/plant - year*$^{-2}$	$K_1 = \mu_1 A^{\mu_2}$	μ_1 and μ_2: A, species, first or stump growth	Valid up to about 30 ft^2/plant. μ's also depend on growing conditions.	±10 to 15
Limiting parameter, K_2 - $year^{-2}$	$K_2 = \eta_1\ A^{\eta_2}$	η_1 and η_2: A, species, first or stump growth	Valid up to about 30 ft^2/plant. η's also depend on growing conditions.	can be large
Asymptotic yield per plant, $K_1/2K_2$-oven-dry lb/plant for n ∞	$\frac{K_1}{2K_2} = \gamma_1\ A^{\gamma_2}$	γ_1 and γ_2: A, often independent of species or harvest cycle	Valid up to about 30 ft^2/plant. γ's also depend on growing conditions.	Generally ±10 to 15
Influence of climate on plantation site productivity	Equations C-41 and C-42	A and insolation and temperature profile during growing season	Depends also on soil character and moisture supply	±15?

TABLE C-XIX (continued)

SUMMARY OF CORRELATIONS APPLICABLE TO DECIDUOUS-SPECIES PLANTATION*

*The definition of symbols not defined in the table are:

A: area per plant at planting, square feet; $A = 43560\ ft^2$ per acre/N_o

n: growing period in years counted from the planting or from the previous harvest

N_o: number of plants per acre at planting

Greek letters: empirical parameters

The correlations which have been developed from experimental data for relating the factors shown in the first column to variables under the plantation operator's control are listed in the second column. The correlations in the second column also involve a number of empirical parameters which are themselves functions of variables under a plantation operator's control. These second-order dependences are identified in the third column in the following way, using entries in the first line of the table as an example:

> parameter a is a function of the planting area per plant A--
> this finding is represented in the third column as
>
> a: A

While the planting area per plant A is the most widely influential variable under the plantation operator's control, others which may have substantial influence on the performance of plantations and, hence, also on the values for some of the empirical parameters are:

- the species grown; and
- whether the plant material is the first produced by the plant or whether it is regrowth from stumps remaining from a previous harvest ("first or stump regrowth" in the table).

The "comments" column includes two classes of entries. One of these is variables for which, while they have a bearing on the performance of plantations, the effect is less well defined or less marked than is the effect of the variables listed in the "variables" column. The second class of entries is limitations on the validity of the correlations.

The fifth column provides estimates of the order of magnitude of errors in harvestable yields which may be introduced by relying on the correlations shown in the table. Errors are expressed as the range in percent of the probable yield which is likely to be achieved in practice. The error ranges have been estimated from a comparison of actual yield data with estimates of the corresponding yields made by backcalculating from the correlations (see Table C-IV for an example). It will be seen that, except for the case of the limiting parameter K_2, the error estimates are generally less than plus or minus fifteen percent. Such an error range is within the range of fluctuations from year to year caused by natural variations in growing conditions.

V. APPLICATION OF THE DECIDUOUS-SPECIES GROWTH MODEL

The correlations established in section IV of this appendix to describe harvestable yields in Energy Plantations may be used in several ways. Examples of these uses pertinent to Energy Plantations at troop training centers are the subject of this section of the appendix.

V.A. Analysis of Limited Experimental Data.

V.A.1. Introduction and Summary Conclusions. As has been indicated previously, much of the experimental data available are too limited to be interpreted by the general methods described in section IV. These valuable but limited data in many cases are a single item of data--for instance, a single harvested yield at a particular planting age. The general analytical method developed in section IV for determining the K and other parameters require at least two harvested yields at the same planting density at two different planting ages.

General relationships between the significant parameters used to describe plant growth -- $K_1/2K_2$, K_1 and K_2 - and the area A per plant at planting have been established (see Table C-XIX). If the initial planting density N_0 is known for an experimentally determined harvested yield, any of the three general relationships can be used to estimate one of the parameters, $K_1/2K_2$, K_1 or K_2. Using this estimated value for one of the K parameters and the experimentally determined yield, a second K parameter can be approximately estimated, and then with the two K parameters so estimated the growing characteristics of a plantation site and species can be roughly evaluated. The preferred procedure for this purpose is the subject of this subsection.

V.A.2. Method. Given one experimental yield, Y_n, in pounds per acre at a planting density , A, square feet per plant, and growing age, n, years, the first step is to estimate yn, the oven-dry harvested wieght per living plant. If the survival rate at year n is not known, the general expression for N_n (see Table C-XIX) can be used, and in this case

$$y_n = \frac{Y_n}{N_n} \times r \quad \text{dry pounds per living plant (C-43)}$$

where Y_n = harvested weight per acre (dry or green)

r = ratio dry weight to green weight

N_n = number of surviving plants at harvest time - if not known experimentally, $N_n = N_o\ 10^{-an}$ can be used (see Table C-II)

Three possible procedures are now open. They are:

1. From $K_1/2K_2 = \alpha_1 A^{\alpha_2}$ (equation C-26) determine the value of $K_1/2K_2$ to be used in the case of interest. Then, determine K_2 from

$$y_n = \frac{K_1}{2K_2} (1 - e^{K_2 n^2}) \qquad \text{(C-8)}$$

which by rearrangement becomes:

$$K_2 = \frac{-1}{n^2} \ln (1 - y_n/K_1/2K_2 \qquad \text{(C-44)}$$

The growth characteristics of the system can then be described by $K_1/2K_2$ and K_2 for other harvest schedules.

2. From $K_1 = \mu_1 A^{\mu_2}$ (equation C-17), determine the value of K_1 for the planting area of interest, Then, using

$$y_n = \frac{K_1}{2K} \quad (1 - \quad {}^{-K_2n^2}) \qquad \text{(C-8)}$$

determine K_2, through $\frac{2y_n}{K_1} = \frac{1-e^{-n^2K}}{K_2}{}_2$ (C-45)

The system is then completely described by the set of parameters K_1 (from the general relation) and K_2 (from the experimental data).

3. Using $K_2 = \mu^1 A^{\mu 2}$, (equation C-23), devise the value of K relevant to the case studied. Then, K_1 is determined from

$$y_n = \frac{K_1}{2K_2} \quad (1-e^{-K_2n^2}) \quad \text{through } K_1 = \frac{2K_2y_n}{1-e^{-n_2K_2}} \qquad \text{(C-46)}$$

Thus giving the two parameters K_1 and K_2 needed to describe the system.

Because of the approximate nature of each of the general relations for $K_1/2K_2$, K_1 and K_2, the values of the sets of K parameters obtained by the three approaches just described will be somewhat different from one another. As a result, the precision with which the experimental data are described will also vary.

A comparison between experimental data and estimates made by each of the procedures just described has been made for two sets of rather extensive experimental data to evaluate the reliability of each of the procedures. One of the data sets is for first harvests from hybrid poplar from clone NE-388 planted at four square feet per plant[18]. The other is for sycamore, again first harvests, planted at four square feet per plant[21].

Values for K_1 and K_2 for first harvests in years two through five were determined from the experimental data using the computer method described by equations C-9 through C-12. Then, using the yield per plant for year two as a hypothetical single experimental item of data,values for K_1 and K_2 were calculated by each of the approximate methods just described.

These approximate K values were then used to estimate harvestible yields in years three through five since planting. These yield estimates were compared with the experimentally determined yields and the difference between them and the experimental yields are reported as "errors" expressed as a percentage of the experimentally determined yields. The results of these calculations and their "errors" are summarized in Table C-XX. For both cases (poplar and sycamore) the columns headed "based on $K_1/2K_2$" correspond to the first approximate method described, and those headed by "based on K_1" correspond to the second and so forth. The underlined values in each column are those obtained directly from the general relationships between planting area per plant A and K_1, K_2 and $K_1/2K_2$ used in the approximate methods. The values not underlined were obtained from the hypothetical single data point and a K value determined directly from one of the general relationships.

For the approximate methods used for the hybrid poplar, the following general correlations for the K parameters were used:

- approximate method 1: for $K_1/2K_2$ - equation C-27
- approximate method 2: for K_1 - line H in Figure C-XVII (the "hybrid poplar - all clones" line), and
- approximate method 3: for K_2 - line B in Figure C-XXIV (the "hybrid poplar - all clones" line).

TABLE C-XX

ILLUSTRATIVE SUMMARY OF ERRORS INTRODUCED IN HARVESTIBLE YIELD ESTIMATES DERIVED FROM DATA FOR ONE HARVEST

	Hybrid Poplar NE-388 Musser, Pa. 4 sq. ft. per plant (Reference 1) Based on:				Sycamore-Fertilized 4 sq. ft. per plant (Reference 21) Based on:			
	$K_1/2K_2$ Method 1	K_1 Method 2	K_2 Method 3	Average (Methods 1 and 3 only	Method 1	Method 2	Method 3	Average (Methods 1 and 2 only
K_1	0.377	0.449	0.379	0.378	1.467	1.385	1.153	1.426
K_2	0.0340	0.1270	0.0375	0.0358	0.171	0.139	0.0415	0.155
$K_1/2K_2$	5.534	1.770	5.057	5.284	4.289	4.986	13.907	4.601
Age of Stand at Harvest	"Errors" in Estimated Harvest Yields Percent of Experimental Values				Errors in Estimated Harvest Yields Percent of Experimental Values			
3 years	-1.7	-18.9	-2.5	-2.1	-11.3	- 6.3	14.0	- 8.9
4 years	-3.9	-36.4	-5.6	-4.8	-20.9	-12.3	33.0	-16.8
5 years	-6.4	-49.9	-9.2	-7.8	-27.0	-16.6	54.9	-22.2

Note: The underlined values are the K estimates derived from general relationships between planting area per plant and K_1, K_2 or $K_1/2K_2$.

It is apparent from Table C-XX that the approximations based on $K_1/2K_2$ (method 1) and K_2 (method 3) for the hybrid poplar give very good results. The larger error in the case of method 2 (based on K_1) is due to the fact that the K_1 line for clone NE-388 differs significantly from the "hybrid poplar - all clones" line, and use of the latter introduces a substantial error. The K_1 line for hybrid poplar NE-388 (line G in Figure C-XVIII) could have been used with better results, but the purpose of the present example is to see what error is introduced when broadly general relationships are used. It is evident that the parameters K_2 and $K_1/2K_2$, and to a certain extent K_1 also, estimated on the basis of K_1 (method 2) are significantly different from the corresponding estimates based on the general relationships for K_2 and $K_1/2K_2$ as a function of planting area per plant A. It is also evident from the "errors" for hybrid poplar shown in the lower part of Table C-XX that the estimates based on methods one and three are more reliable than those based on method two. Consequently, the method two estimates have been omitted from the average values for the K factors shown in Table C-XX.

For the approximate methods used for sycamore, the following general correlations for the K parameters were used:

- approximate method 1: for $K_1/2K_2$ - line F in Figure C-XXV (the "fertilized-second harvest" line),
- approximate method 2: for K_1 - line C in Figure C-XVIII (the "fertilized-first harvest" line), and
- approximate method 3: for K_2 - line D in Figure C-XXIV (the "all plantings-first harvest" line).

It is apparent from the table that the values of the K parameters derived from method three are quite different from those from the other two methods.

TABLE C-XXI

EXPERIMENTAL DATA WHERE ONLY ONE HARVEST YIELD PER PLANTING IS AVAILABLE

Species	Location	Planting Spacing ft x ft	Harvest	Age at Harvest*	Yield o. d. tons/acre	Plant survival to harvest - percent
Silver Maple	Tuttle, Kansas	1 x 4	1st	2	5.6	98
		2 x 4	1st	2	4.9	93
		4 x 4	1st	2	2.9	97
		1 x 4	2nd	2	8.4	82
		2 x 4	2nd	2	9.4	77
		4 x 4	2nd	2	8.6	91
	Milford, Kansas	1 x 4	1st	2	4.4	99
		2 x 4	1st	2	3.7	100
		4 x 4	1st	2	2.6	100
Cottonwood, Missouri	Tuttle, Kansas	1 x 4	1st	2	4.0	85
		2 x 4	1st	2	5.4	95
		4 x 4	1st	2	4.2	94
	Milford, Kansas	1 x 4	1st	2	4.6	87
		2 x 4	1st	2	3.6	82
		4 x 4	1st	2	3.3	91
Cottonwood, Sioux Male	Tuttle, Kansas	1 x 4	1st	2	6.5	98
		2 x 4	1st	2	5.5	99
		4 x 4	1st	2	5.9	100
	Milford, Kansas	1 x 4	1st	2	7.0	97
		2 x 4	1st	2	6.8	100
		4 x 4	1st	2	5.2	100

* Years since planting in the case of first harvests and since the first harvest in the case of second harvests.

Source: Reference 4

Such is not entirely surprising because, as previously noted, the K_2 versus A correlation is rather poor for sycamore. The method three estimates of the K parameters have been ommitted from the average values shown in Table XX.

Thus, when data for only one harvest are available from a planting, it is suggested that the K paramaters be estimated by each of the three approximate methods, then eliminating from consideration any method which leads to values particularly different from those from the other two. The averages of the uneliminated values should be used.

<u>V.A.3. Data Interpreted</u>. An example of using the three approximate methods for estimating K parameters is the subject of this sub-section. The data are for harvests taken two years after planting, or two years after the first harvest in some cases, from plantings of silver maple and two varieties of cottonwood sites in the vicinity of Manhattan, Kansas[14].

The experimental data are given in Table C-XXI.

The procedure for estimating the K values will be developed in detail for the first harvest taken two years after planting from the silver maple stand at one foot by four feet spacing at Tuttle. The results from these calculations and for those from the other stands shown in Table C-XXI are summarized in Table C-XXII.

Estimate the yield per living plant at harvest time:

$$y_n = Y_n / (N_o \times \text{survival rate}) \qquad \text{(C-47)}$$

$= 5.6 \times 2{,}000/\ (10{,}890 \times 0.98)$

$= 1.049$ dry pounds per plant

Note that the harvest data are given on an oven-dry basis, and therefore no adjustments need be made for moisture content.

Estimate K parameters by approximate method one:

$$\frac{K_1}{2K_2} = 0.95815\ A^{1.26494} \qquad \text{(C-27)}$$

$$= 0.95815 \times 4^{1.26494}$$

$= 5.533$ dry pounds per plant

$$K_2 = \frac{-1}{n^2} \ln\left[1 - y_n/(K_1/2K_2)\right] \qquad \text{(C-44)}$$

$$= -1/4 \ln\left[1 - \frac{1.049}{5.533}\right]$$

$$= 0.0526$$

$$K_1 = 5.533 \times 2 \times 0.0526 = 0.582$$

Estimate K parameters by approximate method two:

Correlations between K_1 and the planting area per plant A are the starting point for this method, but correlations are not available for the cottonwood varieties or silver maple for which harvest data are available. Therefore, correlations for similar species must be used, as follows:

- for the two cottonwoods - first harvest - line F in Figure C-XVIII (the "cottonwood" line);

- for silver maple - first harvest - two correlations are used because no suitable guiding information about silver maple growth is available -- the correlations are:

    line F in Figure C-XVIII (the "cottonwood" line),and

    line G in Figure C-XVIII (the "hybrid poplar NE-388" line; and

- for second harvests - assume the ratio of the K_1's for second harvests to K_1's for first harvests conforms to equation C-21.

Thus the estimated values for K_1 are:
from line F:

$$K_1 = 0.34478A^{0.72124} = 0.937 \tag{C-48}$$

from line G:

$$K_1 = 0.16257A^{0.73294} = 0.449 \tag{C-49}$$

The values of K_2 corresponding to these two estimates of K_1 are determined from:

$$y_n = \frac{K_1}{2K_2} \left(1-e^{-K_2 n^2}\right) \tag{C-8}$$

and K_2 corresponding to K_1 equal to 0.937 is found to be 0.325, and less than 0.001 for the K_1 value of 0.449.

The value for $K_1/2K_2$ is 1.442 for the value of K_1 equal to 0.937, and the value corresponding to K_1 equal to 0.449 is very large.

Estimate K parameters by approximate method three:

Correlations between K_2 and the planting area per plant A are the starting point for this method, and the same problem arises in this case as for method two. Consequently the following correlations are used for estimating K_2:

- for the two cottonwoods - first harvest - line E in Figure C-XXIV (the "cottonwood" line),
- for silver maple - first harvest - two correlations are used because no suitable guiding information about silver maple growth is available -- the correlations are:

  line E in Figure C-XXIV (the "cottonwood" line), and
- for second harvests - assume the ratio of K_2's for second harvests to K_2's for first harvests conforms to equation C-24.

Thus the estimated values for K_2 are:
from line E:

$$K_2 = 0.04157A^{-0.34881} = 0.0256 \qquad \text{(C-50)}$$

from line C:

$$K_2 = 0.04389A^{-0.11357} = 0.0375 \qquad \text{(C-51)}$$

The values of K_1 corresponding to these two estimates of K_2 are determined from

$$y_n = \frac{K_1}{2K_2}\left(1 - e^{-K_2 n^2}\right)$$

and are found to be 0.552 for the K_2 value equal to 0.0256, and 0.565 for the value equal to 0.0375.

It will be seen from Table C-XXII, and as noted in section V.A.2., that the three approximate methods do not give similar values for the K parameters. The estimates of the K parameters from methods one and three are fairly similar, but the estimates from method two are generally quite different from those provided by methods one and three. It will also be noted that the estimates of the parameter K_2 derived from approximate method two in five of the seven combinations of species, site, and harvest number shown in Table C-XXII do not follow the expected trend with planting area per plant. The expected trend (see section IV.B.7.a.) is a decrease in the value of K_2 with increasing planting area per plant. The K_2 estimates from methods one and three generally conform to this expectation. The estimates for $K_1/2K_2$ derived from method two do not fit the general correlation shown in Figure C-XXVI. The estimates be method two lie substantially below the regression line, whereas the estimates from methods one and three are astride it. Finally the validation results shown in Table C-XX indicate that method two is the least reliable of the three approximate methods for estimating K factors.

In the light of these various considerations, the averages of the K parameter values derived from methods one and three will be used for plantation planning with respect to silver maple and the two cottonwood varieties until more extensive harvestible yield data become available for the species.

Despite the decision set forth in the preceding paragraph, there is some evidence which suggests that evaluation of the merit of the K parameter estimates derived from each of the approximate methods should be made by assessing the three parameter estimates derived from a particular method as a group, rather than individually. This point is illustrated in Table

C-XXII. The averages of the K parameter estimates shown in Table C-XXII from approximate methods one and three are tabulated along with the averages of the estimates from all three methods. The average values of K_1 and K_2 based on methods one and three, and on all three methods, have been used to backcalculate estimated harvest yields per plant for the two-year-old first harvests and second harvests shown in Table C-XXII. These estimated harvests per plant have been compared with the experimentally determined values shown in the fifth column from the left in Table C-XXII. The differences between the backcalculate estimates and the experimental values are recorded as percentages of the experimental values in the columns headed "estimate variance" in Table C-XXII. It will be seen that these variances are essentially zero for estimates based on averages of K values from methods one and three and are not often very consequential for the estimates based on averages of K values from all three methods. Note also that the variances for silver maple from estimates made from the cottonwood and hybrid poplar correlations are approximately equal.

A regression analysis of the average K parameter estimates based on methods one and three shown in Table C-XXII has been made to determine appropriate μ, γ and α values for future use in equations C-17, C-23 and C-26 with respect to silver maple and the cottonwood varieties. The mean values for these factors and associated standard derivations are shown in Table C-XXIV.

V.A.4. Conclusions. It is reasonably evident that where only one measured harvest yield is available for a combination of site, species and harvest number, the approximate methods described in section V.A.2. can be used in conjunction with K parameter correlations (such as Figures C-XVIII and C-XXIV and equation C-27) with some confidence for estimating K parameters. Estimated K parameters based on method two appear to be less reliable than those based on methods one and three or the averages of K paramater estimates derived from them. The approximate methods are effective means for including

TABLE C-XXII

K PARAMETERS ESTIMATED BY APPROXIMATE METHODS FOR SILVER MAPLE AND TWO COTTONWOOD VARIETIES GROWN AT TWO SITES IN KANSAS-HARVESTS TWO YEARS AFTER PLANTING AND AFTER FIRST HARVEST

Species	Site	Planting area sq. feet	Harvest	Harvested per plant dry lbs.	Approximate Method One K_1	Approximate Method One K_2	Approximate Method One $K_1/2K_2$	Approximate Method Two K_1	Approximate Method Two K_2	Approximate Method Two $K_1/2K_2$	Approximate Method Three K_1	Approximate Method Three K_2	Approximate Method Three $K_1/2K_2$
Silver Maple (see note 1)	Tuttle	4	1st	1.049	0.582	0.0526	5.534	0.937	0.325	1.443	0.552	0.0256	10.770
		8	1st	1.935	1.046	0.0393	13.298	1.545	0.256	3.023	1.007	0.0201	25.015
		16	1st	2.197	1.138	0.0178	31.958	2.547	0.502	2.538	1.133	0.0158	35.868
	Tuttle	4	2nd	1.881	1.150	0.1039	5.534	6.467	1.716	1.884	1.352	0.1937	3.489
		8	2nd	4.484	2.735	0.1028	13.298	12.570	1.396	4.502	2.894	0.1335	10.837
		16	2nd	6.974	3.934	0.0615	31.958	24.483	1.750	6.981	4.167	0.0920	22.661
	Milford	4	1st	0.816	0.442	0.0400	5.534	0.937	0.495	0.947	0.429	0.0256	8.377
		8	1st	1.359	0.717	0.0270	13.298	1.545	0.488	1.584	0.707	0.0201	17.567
		16	1st	1.910	0.985	0.0154	31.958	2.547	0.608	2.094	0.986	0.0158	31.192
Silver Maple (see note 2)	Tuttle	4	1st	1.049				0.449	Note 3	Note 3	0.565	0.0375	7.534
		8	1st	1.935	Same As Above			0.746	Note 3	Note 3	1.036	0.0347	14.949
		16	1st	2.197				1.240	0.621	9.988	1.170	0.0320	18.267
	Tuttle	4	2nd	1.881				3.099	0.788	1.965	1.573	0.2834	2.774
		8	2nd	4.484	Same As Above			6.073	0.621	4.893	3.428	0.2299	7.458
		16	2nd	6.974				11.900	0.821	7.246	4.947	0.1864	13.268
	Milford	4	1st	0.816				0.449	0.049	4.630	0.439	0.0375	5.860
		8	1st	1.359	Same As Above			0.746	0.048	7.840	0.728	0.0347	10.498
		16	1st	1.910				1.240	0.137	4.534	1.018	0.0320	15.886

TABLE C-XXII (continued)

K PARAMETERS ESTIMATED BY APPROXIMATE METHODS FOR SILVER MAPLE AND TWO COTTONWOOD VARIETIES GROWN AT TWO SITES IN KANSAS-HARVESTS TWO YEARS AFTER PLANTING AND AFTER FIRST HARVEST

Species	Site	Planting area sq. feet	Harvest	Harvested per plant dry lbs.	Approximate Method One			Approximate Method Two			Approximate Method Three		
					K_1	K_2	$K_1/2K_2$	K_1	K_2	$K_1/2K_2$	K_1	K_2	$K_1/2K_2$
Cottonwood Sioux Male	Tuttle	4	1st	1.218	0.688	0.0622	5.534	0.937	0.234	2.007	0.641	0.0256	12.501
		8	1st	2.041	1.108	0.0416	13.298	1.545	0.224	3.447	1.062	0.0201	26.377
		16	1st	4.335	2.329	0.0364	31.958	2.547	0.083	15.36	2.237	0.0158	70.783
Cottonwood Sioux Male	Milford	4	1st	1.325	0.758	0.0684	5.534	0.937	0.185	2.539	0.697	0.0256	13.602
		8	1st	2.498	1.383	0.0520	13.298	1.545	0.111	5.990	1.300	0.0201	32.285
		16	1st	3.821	2.035	0.0318	31.958	2.547	0.151	8.417	1.971	0.0158	62.385
Cottonwood Missouri	Tuttle	4	1st	0.864	0.470	0.0424	5.534	0.937	0.454	1.032	0.455	0.0256	8.870
		8	1st	2.088	1.136	0.0427	13.298	1.545	0.211	3.666	1.087	0.0201	26.988
		16	1st	3.283	1.732	0.0271	31.958	2.547	0.238	5.342	1.694	0.0158	53.604
	Milford	4	1st	0.471	0.534	0.0482	5.534	0.937	0.375	1.250	0.511	0.0256	9.966
		8	1st	1.613	0.860	0.0323	13.298	1.545	0.370	2.088	0.839	0.0201	20.844
		16	1st	2.664	1.391	0.0218	31.958	2.547	0.369	3.456	1.375	0.0158	43.506

Notes: 1. Method two and three estimates based on line F, Figure C-XVIII and line E, Figure C-XXIV, respectively.
2. Method two and three estimates based on line G, Figure C-XVIII and line C, Figure C-XXIV, respectively.
3. K_2 estimates are smaller than 0.0001 and the $K_1/2K_2$ estimates are very large.

Source: The information in the first five columns of this table is from reference 14.

TABLE C-XXIII

AVERAGES OF K PARAMETER ESTIMATES FROM TABLE C-XXII AND ESTIMATE VARIANCES BETWEEN BACKCALCULATE HARVEST YIELDS AND EXPERIMENTAL YIELDS SHOWN IN TABLE C-XXII

Species	Site	Planting area sq. feet	Averages - Methods One and Two				Averages - All Three Methods			
			K_1	K_2	$K_1/2K_2$	Est. Var.*	K_1	K_2	$K_1/2K_2$	Est. Var.*
Silver Maple (note 1)	Tuttle (1st harvest)	4	0.567	0.0391	7.250	0	0.690	0.1343	2.571	2
		8	1.026	0.0297	17.266	0	1.199	0.1050	5.712	1
		16	1.136	0.0168	33.746	0	1.606	0.1785	4.500	5
	Tuttle (2nd harvest)	4	1.251	0.1488	4.203	0	2.989	0.6712	2.227	10
		8	2.814	0.1182	11.908	0	6.066	0.5441	5.574	10
		16	4.051	0.0768	26.389	0	10.845	0.6345	8.546	13
	Milford (1st Harvest)	4	0.435	0.0328	6.646	0	0.603	0.1867	1.614	4
		8	0.712	0.0235	15.123	0	0.990	0.1782	2.777	4
		16	0.985	0.0156	31.570	0	1.506	0.2131	3.534	6
Silver Maple (note 2)	Tuttle (1st harvest)	4	0.573	0.0450	6.366	0	--	--	--	-
		8	1.041	0.0370	14.072	0	--	--	--	-
		16	1.154	0.0250	23.155	0	1.183	0.0373	15.851	0
	Tuttle (2nd harvest)	4	1.361	0.1936	3.514	1	1.940	0.3919	2.476	4
		8	3.082	0.1663	9.263	0	4.079	0.3177	6.418	3
		16	4.440	0.1240	17.907	0	6.927	0.3564	9.718	6
	Milford (1st harvest)	4	0.441	0.0387	5.692	0	0.443	0.0420	5.278	0
		8	0.722	0.0308	11.723	0	0.730	0.0364	10.030	0
		16	1.001	0.0237	21.107	0	1.081	0.0614	8.801	0

TABLE C-XXIII (continued)

AVERAGES OF K PARAMETER ESTIMATES FROM TABLE C-XXII AND ESTIMATE VARIANCES BETWEEN BACKCALCULATED HARVEST YIELDS AND EXPERIMENTAL YIELDS SHOWN IN TABLE C-XXII

			Averages - Methods One and Two				Averages - All Three Methods			
Species	Site	Planting area sq. feet	K_1	K_2	$K_1/2K_2$	Est. Var.*	K_1	K_2	$K_1/2K_2$	Est. Var.*
Cottonwood Sioux Male	Tuttle (1st harvest)	4	0.664	0.0439	7.568	0	0.755	0.1071	3.526	1
		8	1.085	0.0309	17.560	0	1.238	0.0953	6.497	1
		16	2.283	0.0261	43.700	0	2.371	0.0451	26.310	0
	Milford (1st harvest)	4	0.727	0.0470	7.732	0	0.797	0.0929	4.293	1
		8	1.342	0.0361	18.596	0	1.409	0.0609	11.574	0
		16	2.003	0.0238	42.051	0	2.184	0.0663	16.470	0
Cottonwood Missouri	Tuttle (1st harvest)	4	0.462	0.0340	6.789	0	0.621	0.1740	1.783	3
		8	1.111	0.0314	17.684	0	1.256	0.0912	6.886	1
		16	1.713	0.0215	39.930	0	1.991	0.0938	10.616	1
	Milford (1st harvest)	4	0.522	0.0369	7.071	0	0.661	0.1500	2.209	2
		8	0.849	0.0262	16.194	0	1.081	0.1408	3.840	3
		16	1.383	0.0188	36.815	0	1.771	0.1354	6.542	3

* Estimate variance

Note 1: See note 1, Table C-XXII

Note 2: See note 2, Table C-XXII

isolated measured harvest yields (of which there are many) from deciduous species of potential interest for Energy Plantations in the data base available for plantation design.

V. B. Optimization of Energy Plantations.

V.B.1. Introduction and Summary Conclusions. It is evident from the analyses in section IV of this appendix that the rate at which harvestible plant material is produced by deciduous species depends on the planting density and harvest schedule, among other factors. The relationships developed in section IV can be used for selecting the planting density and harvest schedule which will maximize the sustained harvestible yield from a particular species at a given plantation site.

The average annual sustained yield from a plantation is the sum of the yields from each of the harvests taken from a planting divided by the number of years which elapse between plantings. The yield at each harvest between plantings from a species at a particular plantation site can be expressed in terms of the planting area per plant A and the years n which elapse between planting time and the first harvest, and between harvests after the first one from the planting. The average annual sustained yield from a species at a given plantation site is a complex function of A, n, and the number of harvests taken between plantings. Values for these three variables can be determined from the function which maximize the average annual sustained yield from a species-plantation site combination. A computer program has been written for this purpose.

The values for A, n, and the number of harvests taken between plantings which lead to the maximum average annual sustained yield depend on the growing habits of the species under consideration. They depend therefore on the K parameters previously described, which, in turn, depend on cultural treatments, climate and soil character at the plantation.

Developing and demonstrating a procedure for maximizing the average annual sustained yield from plantations is the subject of this subsection.

V.B.2. Method. The average annual sustained yield $\overline{Y}_n$ from a planting in a plantation from which a succession of harvests have been taken during a period of Σn_i years is given by:

$$\overline{Y}_n = \frac{1}{\Sigma n_i} (Y_{n_1} + Y_{n_2} + Y_{n_3} \ldots) \text{ tons per acre-year} \qquad \text{(C-52)}$$

where Σn_i = total number of years elapsed between the time the stand was planted and the time of the last harvest taken from the stand before it must be replaced with a new planting,

n_i = years of growth before the i^{th} harvest, and

Y_{n_i} = yield of i^{th} harvest resulting from a growth period of n_i years - tons/acre.

The yield from each harvest Y_{n_i} is given by

$$Y_{n_i} = N_{n_i} \, y_{n_i} \qquad \text{(C-1)}$$

$$= N_{n_i} \left(\frac{K_1}{2K_2}\right) \left(1 - e^{-K_2 n_i^2}\right) \qquad \text{(C-53)}$$

where N_{n_i} = numbers of living plants at year n_i and

TABLE C-XXIV

RESULTS OF REGRESSION ANALYSES OF K PARAMETERS BASED ON APPROXIMATE METHODS ONE AND THREE IN TABLE C-XXVIII (see Note 3)

Species	Site*	$K_1 = \mu_1 A^{\mu_2}$ equation C-17 μ_1	μ_2	$K_2 = \gamma_1 A^{\gamma_2}$ equation C-23 γ_1	γ_2	$\frac{K_1}{2K_2} = \alpha_1 A^{\alpha_2}$ equation C-26 α_1	α_2
Silver Maple (note 1)	T (1)	0.307 (0.140)	0.501 (0.205)	0.0956 (0.0257)	-0.6094 (0.1232)	1.607 (0.284)	1.110 (0.082)
	T (2)	0.416 (0.171)	0.848 (0.186)	0.2983 (0.0541)	-0.4776 (0.0837)	0.697 (0.155)	1.325 (0.102)
	M (1)	0.198 (0.030)	0.589 (0.069)	0.0697 (0.0050)	-0.5352 (0.0334)	1.419 (0.010)	1.124 (0.036)
Silver Maple (note 2)	T (1)	0.309 (0.141)	0.505 (0.205)	0.0841 (0.0150)	-0.4270 (0.0824)	1.839 (0.493)	0.931 (0.123)
	T (2)	0.450 (0.187)	0.853 (0.188)	0.3097 (0.0375)	-0.3216 (0.0590)	0.7263 (0.0205)	1.175 (0.129)
	M (1)	0.199 (0.030)	0.592 (0.070)	0.0635 (0.0018)	-0.3531 (0.0134)	1.570 (0.190)	0.945 (0.056)
Cottonwood Sioux Male	T (1)	0.185 (0.038)	0.890 (0.106)	0.0715 (0.0118)	-0.3744 (0.0763)	1.295 (0.081)	1.265 (0.029)
	M (1)	0.274 (0.052)	0.731 (0.088)	0.0952 (0.0128)	-0.4909 (0.0621)	1.436 (0.079)	1.222 (0.026)

TABLE C-XXIV (continued)

RESULTS OF REGRESSION ANALYSIS OF K PARAMETERS BASED ON APPROXIMATE METHODS ONE AND THREE IN TABLE C-XXIII (SEE NOTE 3)

Species	Site*	$K_1 = \mu_1 A^{\mu_2}$ equation C-17 μ_1	μ_2	$K_2 = \gamma_1 A^{\gamma_2}$ equation C-23 γ_1	γ_2	$\frac{K_2}{2K_2} = \alpha_1 A^{\alpha_2}$ equation C-26 α_1	α_2
Cottonwood Missouri	T (1)	0.134 (0.055)	0.945 (0.185)	0.0568 (0.0155)	-0.3331 (0.1253)	1.182 (0.152)	1.278 (0.059)
	M (1)	0.197 (0.001)	0.702 (0.001)	0.0726 (01000)	-0.4878 (0.0006)	1.360 (0.011)	1.190 (0.004)

*Site and harvest - T(1) = first harvest at Tuttle, Kansas, T(2) = second harvest at Tuttle
M(1) = first harvest at Milford, Kansas, M(2) = second harvest at Milford.

Note 1: See Note 1, Table C-XXVII

Note 2: See Note 2, Table C-XXVII

Note 3: The upper entry for each site and harvest mean value of the factor and the entry in parenthesis under it is the standard deviation.

y_{n_i} = yield per living plant at year n_i -- the values of the growth parameters $K_1/2K_2$ and K_2 to be used in equation C-53 depend on whether the harvest is the first one taken from the stand or whether it is the second or a later one.

Two assumptions are recalled at this point:

1. The numbers of surviving plants N_{n_i} at the second and subsequent harvests is equal to the number of surviving plants after the first harvest (see section IV.A.8.), and therefore:

$$N_{n_1} = N_{n_2} = N_{n_3} \ldots\ldots\ldots \qquad \text{(C-54)}$$

2. The harvestible yields per plant from second and subsequent harvests are equal providing the intervals between the harvests are equal (see section IV.A.8.), and therefore:

$$y_{n_2} = y_{n_3} \ldots\ldots\ldots \text{ if } n_2 = n_3 = \ldots\ldots\ldots \qquad \text{(C-55)}$$

Accepting these assumptions, equation C-52 becomes:

$$\bar{Y}_n = \frac{N_{n_1}}{(\sum_i^m n_i)} \left(Y_{n_1} + \sum_{i=2}^{m} Y_{n_i} \right) \qquad \text{(C-56)}$$

For the particular case in which all second and subsequent harvests are taken at equal intervals, n_2 years, equation C-56 becomes:

$$\bar{Y}_n = \frac{N_{n_1}}{(n_1 + mn_2)} \left(Y_{n_1} + mY_{n_2} \right) \qquad \text{(C-57)}$$

where m = *number of harvests taken from the stand after the first harvest, and*

n_2 = the interval between harvests after the first harvest.

V.B.3. Computer Program for Optimization. A computer program has been written for the optimization procedure. The program tabulates values of average annual sustained yields estimated in accord with equation C-57 The program listing in focal for a Digital Equipment Corporation PDP 8/I computer is shown in Table C-XXV.

The output from the program is an estimate of that combination of planting density and harvest schedules which maximizes the average annual sustained yield from a particular species. The program also identifies any combinations of planting density and harvest schedule which can be expected to produce at least ninety-five percent and at least ninety percent of the maximum yield. These outputs have been provided from the program because combinations of planting density and harvest schedule may exist which provide sustained yields almost as large as the maximum possible yield, but at less cost. For instance some of the "almost-as-good" yields may require a lower planting density (therefore lower planting cost) or less frequent harvesting (hence possibly lower field costs).

The inputs to the program are:

- cut off limits for yields almost as good as the maximum sustainable yield;
- range of planting areas per plant (the increase of planting density) to be considered - four, eight, twelve and sixteen square feet per plant are usually sufficient for identifying the maximum sustainable yield from a particular species;
- the age of the stand at first harvest (usually one, two and three years is sufficient), and the interval between harvests after the first harvest (one, two, three and four years are often adequate);

- factors for describing parameters K_2 and $K_1/2K_2$ as a function of planting area per plant A, using for K_2:

$$K_2 = \eta_1 A^{\eta_2} \quad \text{(C-23)}$$

(in the program, η_1 and η_2 for first harvests are KAPPA 1 and LAMBDA 1, respectively, and KAPPA 2 and LAMBDA 2 for second and subsequent harvests, respectively); and

for $K_1/2K_2$:

$$K_1/2K_2 = \gamma_1 A^{\gamma_2} \quad \text{(C-26)}$$

(in the program γ_1 and γ_2 for first havests are ALPHA 1 and BETA 1, respectively, and ALPHA 2 and BETA 2 for second and subsequent harvests, respectively); and

- the two parameters for defining the decay factor a in equation C-3.

The number of harvests m after the first harvest from a stand has been set at five in the program because it is known that five harvests subsequent to the first can be taken without loss of regrowth vigor in a stand. It would be beneficial in terms of average annual sustained yield and plantation operating cost to set m a little over five (seven or eight perhaps), but such has not been done in the program because no data have been found on the effect on sustained yield of more than five harvests after the first from a stand.

V.B.4. Example of Optimization Calculation. A step by step description of the optimization procedure is given in this subsection. It is based on hybrid poplar grown from clone NE-388 at Musser Farm in central Pennsylvania:

TABLE C-XXV

PROGRAM LISTING FOR DETERMINING AVERAGE ANNUAL SUSTAINED YIELDS ON THE BASIS OF EQUATION C-56*

```
C-8K FOCAL @1969

01.01 A ! "1ST LEVEL BELOW OPTIMUM" L(0)
01.02 A ! "2ND LEVEL BELOW OPTIMUM" L(1)
01.03 A ! "NO. OF AREAS-PER-TREE'S" NA
01.05 A ! "NO. OF YEAR-OF-FIRST-CUT'S" N1
01.07 A ! "NO. OF YEARS-PER-SUB.-CUT'S" NS
01.09 A ! "ALPHA 1" A1; A "BETA 1" B1
01.11 A ! "ALPHA 2" A2; A "BETA 2" B2
01.13 A ! "KAPPA 1" K1; A "LAMBDA 1" L1
01.15 A ! "KAPPA 2" K2; A "LAMBDA 2" L2
01.20 S YT=0.; S CN=-1
01.22 S PU=0.; S PV=0.; S PW=0.
01.25 D 17

02.01 F IA=1,NA; S PA=PU+IA*4.; D 18

03.01 I (CN)4.01,4.01,6.01

04.01 S CN=CN+1
04.02 T !"SOLUTIONS GREATER THAN",%6.02,L(CN)," OF THE OPTIMUM"
04.03 GOTO 1.22

06.01 GOTO 1.09

07.01 QUIT

17.01 T !" AREA PER TREE FIRST CUT SUB. CUTS "
17.02 T "AVG. ANN. YIELD"

18.01 S PG=FLOG(PA)
18.02 S DP=0.07767*FEXP(-0.390084*PG)
18.03 D 19

19.01 F I1=1,N1; S P1=PV+I1; D 20

20.01 S ST=(43560./PA)*FEXP(-DP*P1*2.30259)
20.02 S Y1=A1*FEXP(B1*PG)*(1.-FEXP(-K1*FEXP(L1*PG)*P1↑2))
20.03 D 21

21.01 F IS=1,NS; S PS=PW+IS; D 22

22.04 S ZQ=ST/(P1+5.*PS)
22.06 S YS=A2*FEXP(B2*PG)*(1.-FEXP(-K2*FEXP(L2*PG)*PS↑2))
22.07 S Y=ZQ*(Y1+5.*YS)/2000.
22.10 I (CN)22.11; GOTO 22.40
22.11 D 23
22.12 I (Y-YT)22.20,22.20,22.30
22.20 RETURN
22.30 T !" NEW OPTIMUM FOUND ",!
22.31 S YT=Y
22.32 RETURN
22.40 I (Y-L(CN)*YT)22.20
22.41 D 23
22.42 RETURN

23.01 T !%7,PA,%11,P1,%9,PS,%13.02,Y
```

*The program is written in FOCAL for a Digital Equipment Corp. PDP-8/I computer.

The input data and their sources are:

- number of surviving plants at the time of first harvest is based on equations C-3 and C-2 -- for equation C-3, the values of α and β are those shown for hybrid poplars in Table C-II -- introduction of these specific values for α and β into the computer program involves a change in the setting in line 18.02 because other more general values for α and β are set in the program as it is shown in Table C-XXV;

- the cutoffs for printing out yields almost as good as the maximum yield were set at ninety-five and ninety percent of the maximum yield, respectively;

- five planting areas per plant were chosen, namely, the multiples of four between four and twenty square feet per plant;

- the ages of the stand at first harvest to be considered in the maximization calculation were set at one, two and three years after planting, and the intervals between harvests after the first harvest were set at one, two, three and four years;

- factors for describing parameters $K_1/2K_2$ and K_2 were selected as follows:

for $K_1/2K_2$: this ratio, the asymptotic yield per plant, was assumed to be the same for growth before the first harvest and for growth between harvests after the first harvest (see page C-116) -- the constants γ_1 and γ_2 (ALPHA and BETA, respectively, in the computer program listing) in equation C-26 relating the ratio to the planting area per plant A were determined by regression analysis of the estimates of $K_1/2K_2$ shown in tables C-V and C-VII (first and second harvests, respectively) for hybrid poplar NE-388 grown at Musser Farm -- the resulting relationship is:

$$K_1/2K_2 = 1.325742\ A^{1.06119} \qquad \text{(C-58)}$$

and 1.325742 was used for ALPHA and 1.06119 for BETA in the computer program; and

for K_2: for growth before the first harvest, the values of η_1 and η_2 given in Table C-XII for hybrid poplar NE-388 grown at Musser Farm were used, and for growth between harvests after the first the corresponding values from Table C-XIII were used -- note that in the computer program listing, α_1 is KAPPA and α_2 is LAMBDA).

The results of running the computer program with these inputs are summarized in Table C-XXVI. The program first prints out the estimated average annual sustained yields for all combinations included in the input information of planting area per plant, planting age at first harvest and intervals between harvests after the first harvest. In the example being discussed, there are sixty such combinations, of which the first six are shown in Table C-XXVI. The highest estimated annual yield is 9.43 dry tons per acre from a planting at four square feet per plant (about 10,900 plants per acre) with the first harvest taken when the planting is one year old and the five subsequent harvests taken at two-year intervals.

The program then prints out all the combinations which are estimated to provide sustained annual yields at least as large as ninety-five percent of the maximum. In this case, there are none. Finally a listing is printed out of all the combinations which are estimated to produce yields greater than ninety percent of the maximum. In this case, besides the maximum, there are seven others, three of which are about 8.8 dry tons per acre per year or about ninety-three percent of the maximum annual sustained yield. Notice that these three are rather different combinations of the input data, namely:

Planting area	Planting age at first harvest	Interval between each of the five subsequent harvests
4	1	3
8	1	2
8	1	3

The form of the results from this example are fairly typical of the results produced by the computer program for numerous combinations of species and proposed plantation sites, although the estimated maximum average annual sustained yield varies considerably among the combinations. Because the results from the example being discussed are broadly typical,they will be examined further.

The estimated average annual yields from all combinations included in the input information in which the area at planting, age at first harvest and the interval between subsequent harvests are equal are shown in Figure C-XXX. That is,n_1 equals n_2 in equation C-57. For convenience, these cases are described as "symmetrical harvest cycles". Estimated annual sustained yields at a planting area of two square feet per tree have been added to the estimates in the figure.

The estimates in Figure C-XXX suggest that when n_1, the age of the stand at first harvest,is only one or two years old in symmetrical harvest cycles, the

TABLE C-XXVI

ESTIMATES OF THE MAXIMUM AND NEAR MAXIMUM AVERAGE ANNUAL SUSTAINED YIELD FROM HYBRID POPLAR NE-388 AT MUSSER FARM DETERMINED BY THE COMPUTER PROGRAM LISTED IN TABLE C-XXV

Planting Area Per Plant Square Feet	Harvest Schedule-Years To First Harvest	Harvest Schedule-Years Between Harvests	Average Annual Yield Dry Tons Per Acre
Excerpt from computer listing of average annual yields from all data computation			
4	1	1	6.37
4	1	2	9.43
4	1	3	8.38
4	1	4	7.19
4	2	1	5.57
4	2	2	8.52
.	.	.	.
.	.	.	.
.	.	.	.
Computer listing of all annual yields greater than 95% of the maximum			
4	1	2	9.43
Computer listing of all annual yields greater than 90% of the maximum			
4	1	2	9.43
4	1	3	8.80
4	2	2	8.52
8	1	2	8.81
8	1	3	8.78
12	1	3	8.69
16	1	3	8.59
20	1	3	8.49

maximum annual sustained yield is reached at planting densities less than two square feet per plant. As n_1 is increased, the optimum planting area per plant increases also, being between six and ten square feet per plant for n_1 equal to three years and twenty to twenty-four square feet for n_1 equal to four years. These observations and the shapes of the curves in the figure reflect several trends arising from the fact that the average annual yield per acre is the sum of the products of the number of plants per acre surviving to each harvest and the weight of harvestable material per plant at each harvest, divided by the total years elapsing while six harvests are reaped.

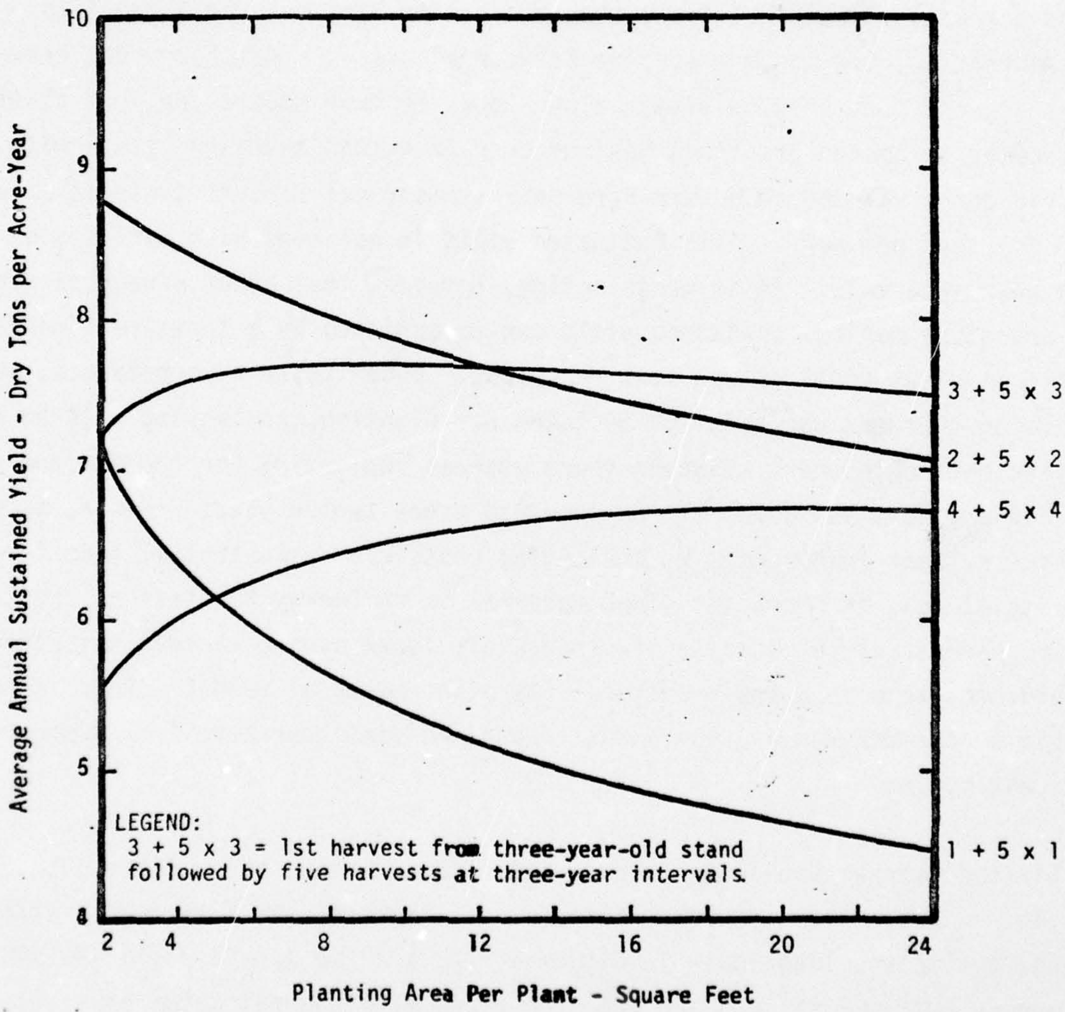
When the time to first harvest and between harvests is short (n_1 and n_2 are equal and one or two years), the fraction of the plants per acre surviving to harvest is large but their individual weight of harvestable material is small, and the opportunity for substantial growth between harvests after the first one is quite limited. Under these circumstances the highest yields will be achieved at high planting density. Moreover, because the average annual yields decline as planting density declines, the decline in plants per acre has greater effect on yield per acre than does the increase in harvestable material per plant made possible by greater land area per plant.

When the interval between harvests is four years, there is time for substantial growth between harvests, a factor which apparently has greater effect on annual yield than does the declining number of plants per acre as planting density is decreased. Consequently, average annual yield increases with reduction in planting density (or increase in planting area per plant). This trend with changes in planting density is the reverse of the corresponding trend when the interval between harvests is only one or two years. However, when the interval is three years, the opposed effects on yield, as planting density is decreased, of fewer plants per acre and increased opportunity for substantial

FIGURE C-XXX

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELDS FROM HYBRID POPLAR NE-388 GROWN AT MUSSER FARM, CENTRAL PENNSYLVANIA, AS A FUNCTION OF PLANTING AREA PER PLANT

Symmetrical Harvest Cycles



production of harvestable material per plant between harvests are approximately in balance, and yield per acre remains nearly constant over a wide range of planting densities.

From a practical point of view, when harvesting machinery is taken into consideration, the minimum spacing between plants is about four feet between rows and one foot between plants along rows, or four square feet per plant. Thus, the estimated practical maximum average annual sustained yield with hybrid poplar NE-388 at Musser Farm on a symmetrical harvest cycle is about 8.5 dry tons per acre. This estimated yield is achieved with harvests at two-year intervals. It is worth noting, however, that about ninety percent of practical maximum sustained yield can be achieved by a three-year harvest cycle at about eight square feet per plant. Under these circumstances, and assuming that six harvests can be taken per planting, replanting will be required only once every eighteen years whereas replanting for the maximum yield of 8.5 dry tons per acre will be required every twelve years. Since, as will become evident in Appendix F, replanting costs are a substantial fraction of the total cost of producing plant material in an Energy Plantation, the three-year harvest cycle, despite its moderately lower average annual sustained yield, may lead to a lower cost for the plant material produced than is possible at the maximum average annual sustained yield per acre from symmetrical harvest cycles.

Estimated average annual sustained yields from various harvest schedules where n_1 and n_2 are not always equal are shown in Figures C-XXXI through C-XXXIII. These estimates, like those in Figure C-XXX, are for hybrid poplar NE-388 grown at Musser Farm, and are from the group of yield estimates partially summarized in Table C-XXVI. It is apparent in each of these figures that the maximum sustained annual yield is achieved at planting areas of four square feet per plant and with two-year intervals between harvests.

The estimated average annual sustained yields at various intervals between harvests for hybrid poplar NE-388 at Musser Farm as a function of the age of the stand at first harvest are shown in Figure C-XXXIV. It is evident, in all cases shown, that the highest sustained yields are achieved when the first harvest is taken from one-year-old stands.

The estimated sustained yields shown in Figure C-XXXIV are plotted as a function of the interval between harvests in Figure C-XXXV. At a planting area of four square feet per plant, sustained yields pass through a sharp maximum at two-year intervals between harvests, but the maximum declines as the age of the stand at first harvest declines. At eight square feet per plant, the maximum yields are displaced toward three-year intervals between harvests, but they also decline as the age of the stand at first harvest is increased.

The estimated average annual sustained yield is a function of the number of harvests taken from a stand after the first harvest. Assuming that a few more than five such harvests can be taken from a stand without loss of yield per harvest, the effect on the average annual sustained yield of varying the number of harvests after the first one is shown in Figure C-XXXVI. It will be seen that as the number of harvests is increased, the rate at which the annual sustained yield increases,declines. For instance, at the planting areas per plant shown in the figure, the average annual sustained yield increases only about four percent by increasing the number of harvests after the first one from five to ten. However, if such an increase in harvests would not cause a loss in yield per harvest (such a loss, if it occurred, would invalidate the estimates shown in the figure), the interval between replanting a stand would be increased from eleven years at five harvests after the first one to twenty-one years at ten harvests after the first. Such a change in replanting schedule would have a substantial beneficial effect on the cost of plant material produced in the plantation.

V.B.5. Conclusions. The procedure for estimating the planting density and harvest schedule which maximize the average annual sustained yield from deciduous tree species is shown to be workable and convenient by its application to a sample case based on hybrid poplar NE-388 grown at Musser Farm in central Pennsylvania. Comparison of its predictions with actual experimental data from Musser Farm shows that its predictions agree fairly closely with the experimental data in reference 1. Moreover, the yield estimates generated by the procedure conform to the general trends expected from the analysis of deciduous-species growth in section IV of this appendix.

FIGURE C-XXXI

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELD FROM HYBRID POPLAR NE-388 GROWN AT MUSSER FARM, CENTRAL PENNSYLVANIA, AS A FUNCTION OF PLANTING AREA PER PLANT

First Harvest One Year After Planting

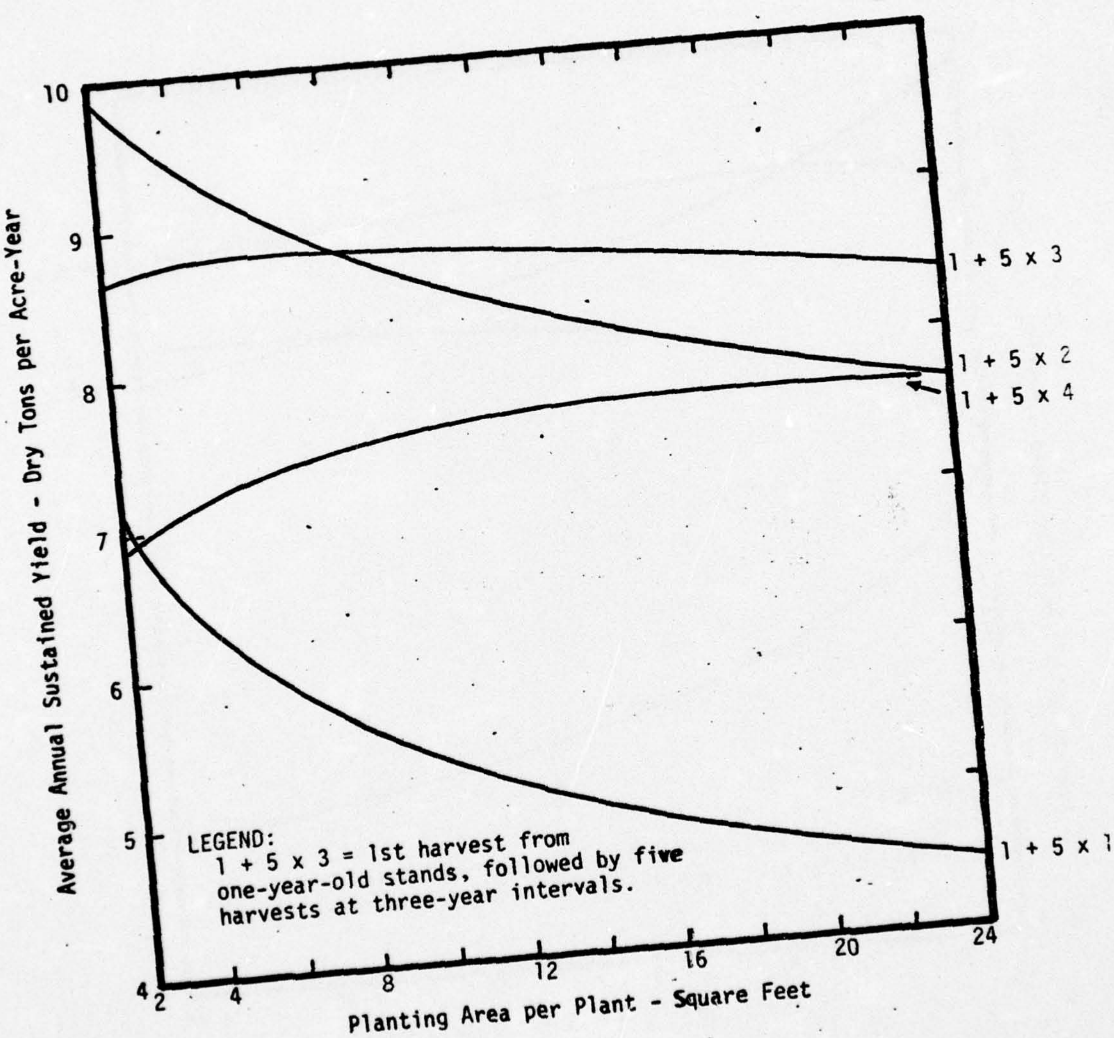


FIGURE C-XXXII

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELDS FROM HYBRID POPLAR NE-388 GROWN AT MUSSER FARM, CENTRAL PENNSYLVANIA, AS A FUNCTION OF PLANTING AREA PER PLANT

First Harvest Two Years After Planting

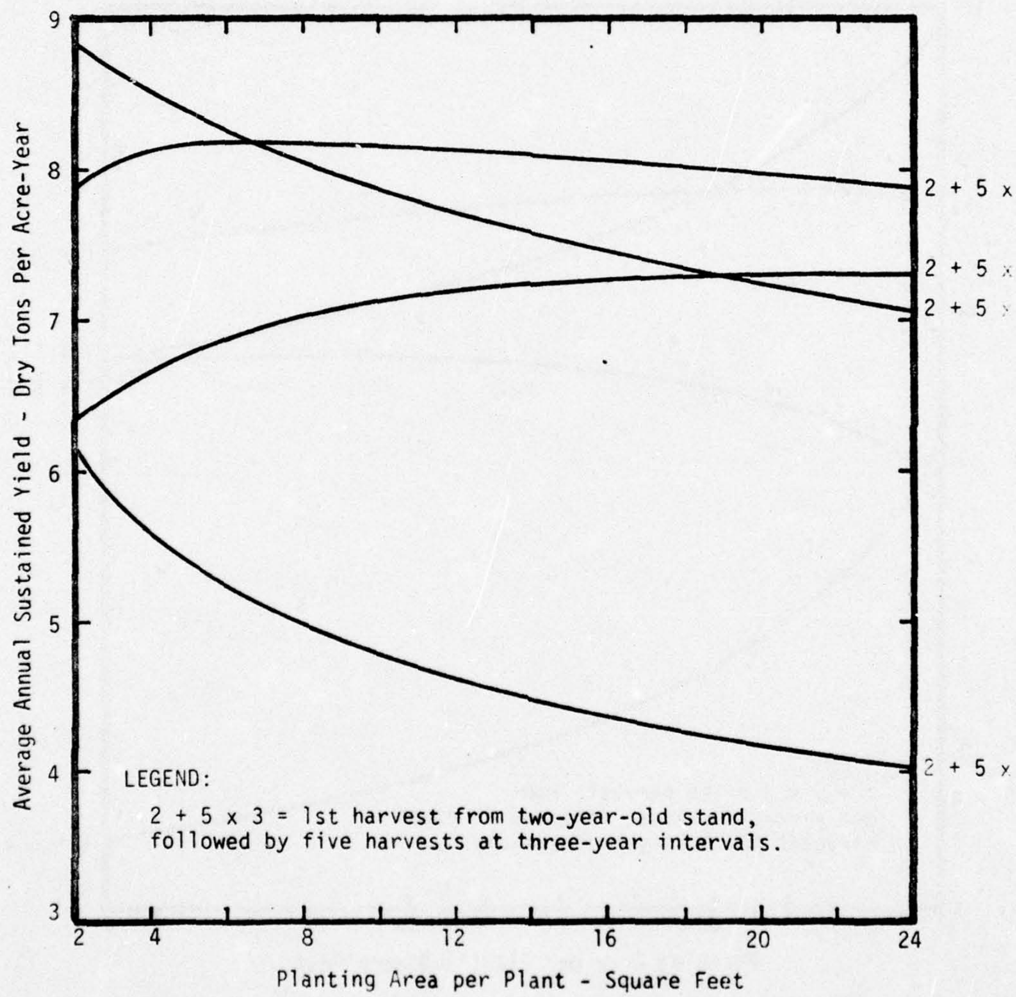


FIGURE C-XXXIII

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELDS FROM HYBRID POPLAR NE-388 GROWN AT MUSSER FARM, CENTRAL PENNSYLVANIA, AS A FUNCTION OF PLANTING AREA PER PLANT

First Harvest Three Years After Planting

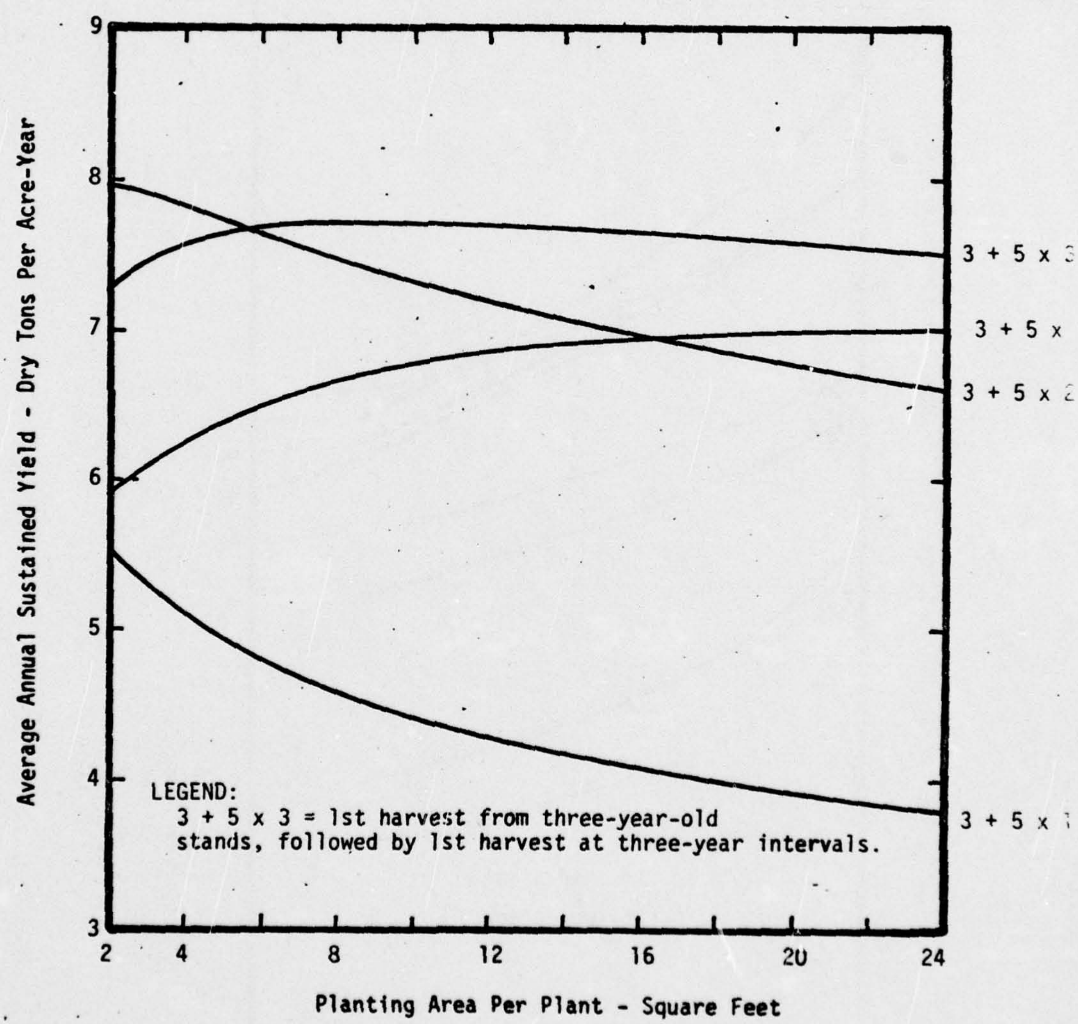


FIGURE C-XXXIV

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELDS FROM HYBRID POPLAR NE-388 GROWN AT MUSSER FARM, CENTRAL PENNSYLVANIA, AS A FUNCTION OF STAND AGE AT FIRST HARVEST

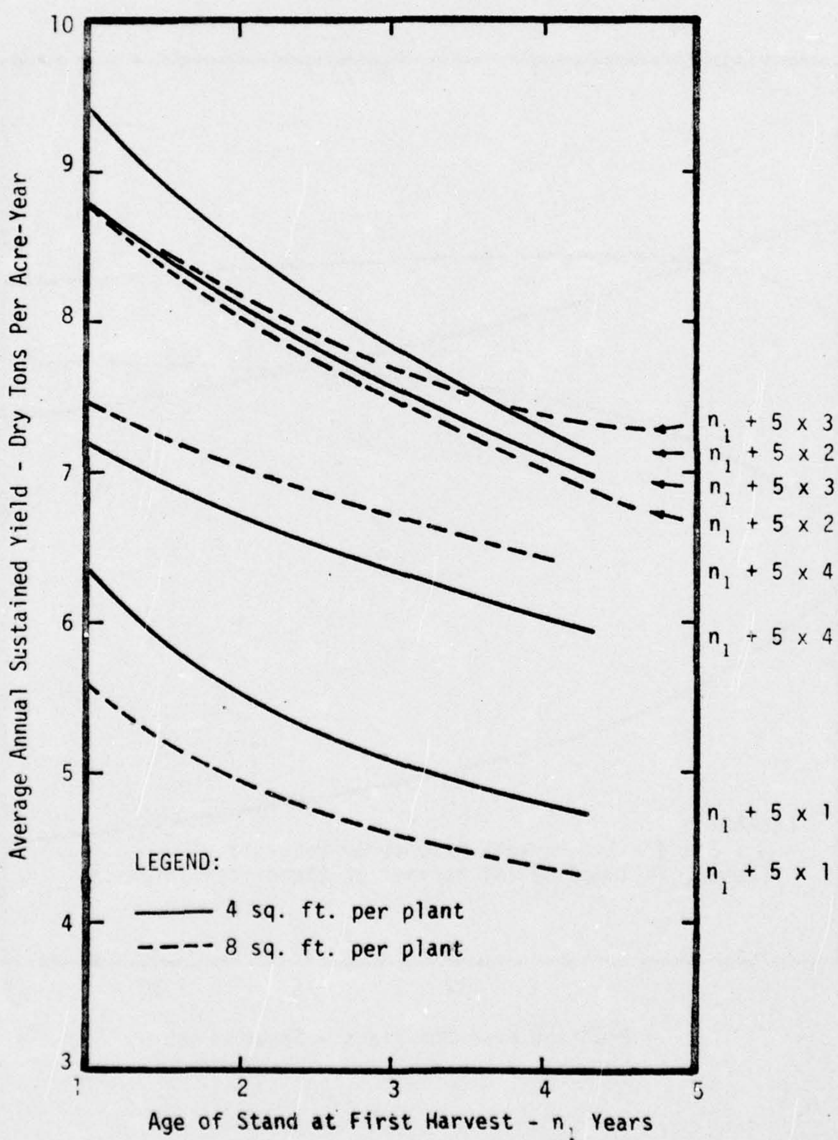


FIGURE C-XXXV

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELDS FROM HYBRID POPLAR NE-388 GROWN AT MUSSER FARM, CENTRAL PENNSYLVANIA, AS A FUNCTION OF INTERVAL BETWEEN HARVESTS

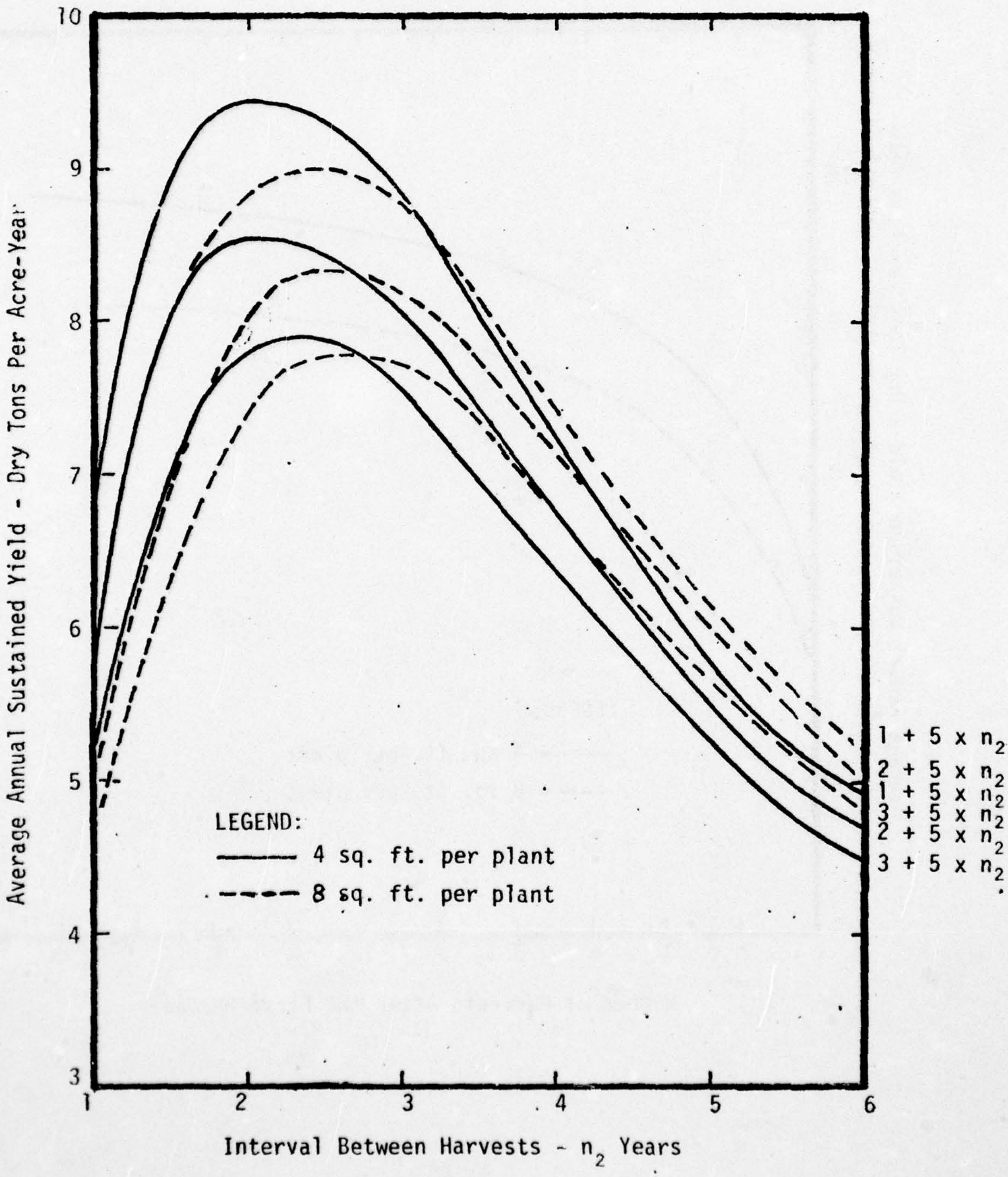
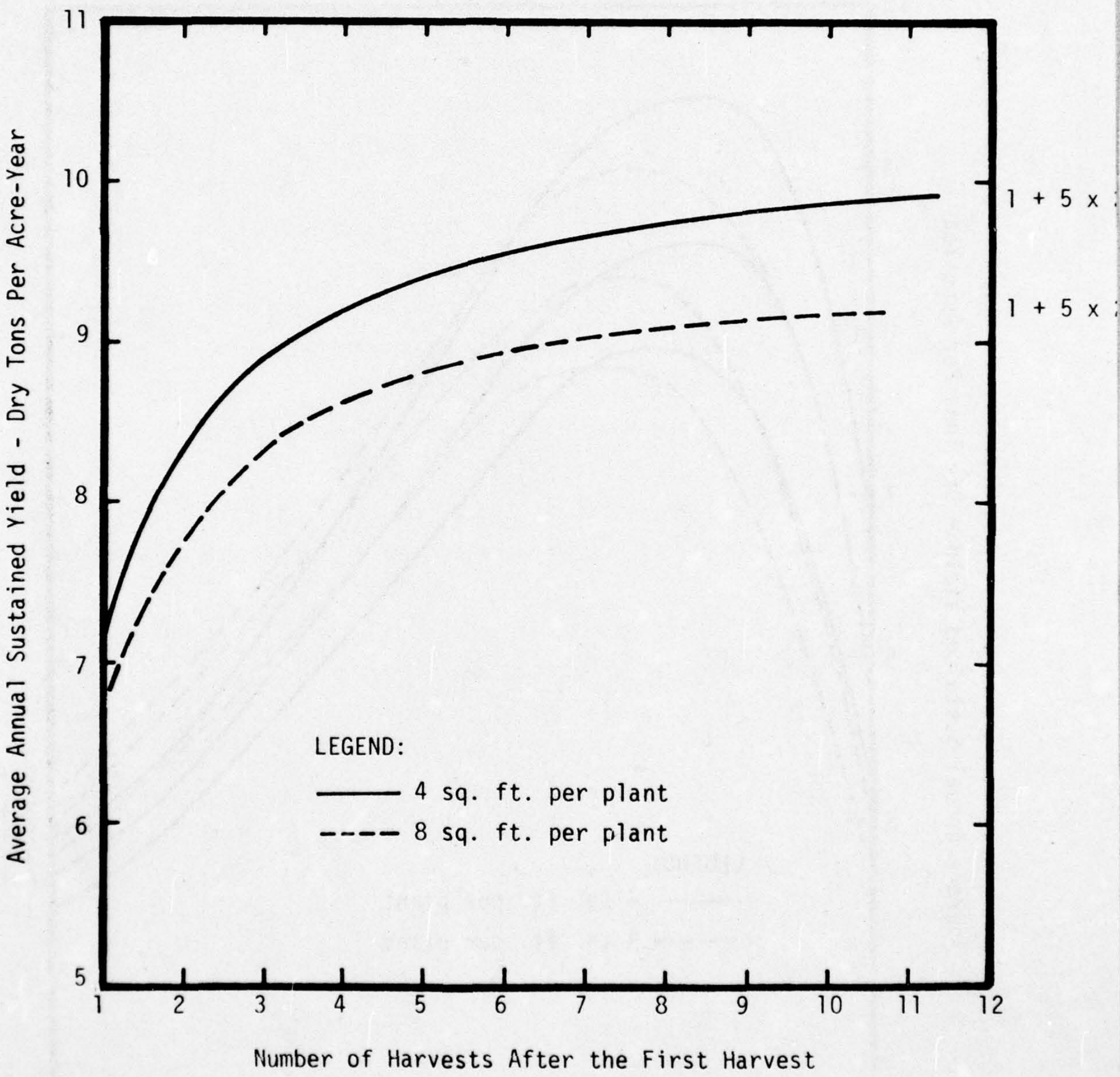


FIGURE C-XXXVI

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELDS FROM HYBRID POPLAR NE-388 GROWN AT MUSSER FARM, CENTRAL PENNSYLVANIA, AS A FUNCTION OF THE NUMBER OF HARVESTS AFTER THE FIRST HARVEST

Age of Stand at First Harvest: 1 year
Interval Between Harvests: 2 years



VI. SENSITIVITY ANALYSIS - PREFERRED PARAMETERS FOR OPTIMIZATION

VI.A. Introduction and Summary Conclusions. The method for estimating and optimizing yields from deciduous species grown in plantations described in section V.B. depends on correlations relating plant growth and survival rates to the planting area per plant and other fundamental factors. The correlations involve a number of parameters for which values have been estimated from the data on the growth and survival of deciduous tree species in stands planted by man. However, because the available data are few and often not very precise, the parameter estimations must be regarded as approximations to their true values. Elements of uncertainty are introduced, therefore, into the average annual sustained yield and other projections made from relationships involving the parameter estimates.

One of the two purposes of this section is to estimate the likely impact of uncertainties in the parameter estimates on projections based on the parameters.

Since there is sometimes a choice of parameters which can be used for making a particular projection, the second purpose of this section is to determine which parameters are to be preferred for making projections when a choice of parameters is available.

It is concluded, on the basis of the analysis in this section, that most projections involving the estimated parameters are unlikely to be more than twenty percent in error.

VI.B. Sensitivity Analysis. Average annual sustained yields are estimated from:

$$\overline{Y}_N = \frac{N_{n_1}}{(n_1 + mn_2)} (Y_{n_1} + mY_{n_2}) \qquad \text{(C-57)}$$

The impact of uncertainty in each of the terms in this equation will be considered.

Number of plants surviving at the time of the first harvest - N_{n_1}. It is apparent from equation C-57 that estimated average annual sustained yields are directly proportional to the value used for N_n. Values for N_{n_1} are estimated from the general equation for the number[1] of plants surviving at the time of the i^{th} harvest:

$$N_{n_i} = N_o \, 10^{-an_i} \qquad \text{(C-2)}$$

and a is estimated from

$$a = \alpha A^{\beta} \qquad \text{(C-3)}$$

Therefore, since the number of plants N_o actually planted in a stand, and therefore also A, are usually known fairly precisely, and because n_i can be defined exactly, any uncertainty in the value of N_{n_i} depends on uncertainties in the values for α and β for a particular species-plantation site combination. Reference to Table C-II indicates that values for α and β vary among such combinations. It is also seen that the values depend on whether the plantation site is cultivated and/or also fertilized. At cultivated sites, the value for α ranges from about 0.03 to 0.11 and is typically about 0.05 (see Figure C-IX). In sites which are fertilized and cultivated, the value for α, based on very limited data, ranges from about 0.20 to 0.25. Values for β, the slopes of the lines in Figure C-VIII, are evidently fairly uniform among species and plantation cultural treatments. Its value is characteristically about minus 0.5. Therefore, uncertainty in the value of N_{n_i} depends primarily on uncertainty in the value used for the factor α. An error of plus or minus twenty percent in the value used for α will introduce an error of less than five percent in the estimate of the number of plants surviving to age three in cultivated stands, and an error of less than fifteen percent in stands which are cultivated and fertilized.

Number of plants surviving to harvests after the first harvest. It is assumed in deriving equation C-57 that the number of plants surviving to the first harvest is maintained during subsequent harvests. There are no systematic data available for validating this assumption. However, people involved in growing deciduous species in dense plantings from which several harvests have been taken, as well as direct observation of plantings by members of InterTechnology's staff, support the approximate validity of this assumption. It is concluded, therefore, that this assumption is unlikely to be a major source of error.

Effect of stand age at first harvest on the rate of regrowth from stumps. In equation C-57, it is assumed that the rate of regrowth from stumps after the first harvest is independent of the age of the plants at the time of the first harvest. This assumption implies that if the first harvest is taken at the end of the first year, for instance, the root system, stump dimensions and other aspects of the unharvested parts of the plant which constitute the base from which regrowth occurs, support plant-material regrowth at the same rate as the comparable parts of a plant do which had not been harvested for the first time until it was two or three years old. The data on regrowth after the first harvest from plants up to three years old are confusing on this point. Some of the data suggest that the rate of regrowth after the first harvest may depend on the age of the plant at the first harvest. Others suggest no such dependence. The existence of a relationship between stump age and rate of regrowth from stumps would not be surprising because one-year-old stumps are smaller in diameter and have a smaller root system than older stumps and, thus, are probably less capable of supporting fast regrowth than are older stumps.

Data for sycamore[23,26] (Figure C-VII) which suggest a possible relationship between the rate of regrowth after the first harvest and the age of the stand at first harvest have been compared, albeit with some misgiving because the data are from a bottomland and an upland site in Georgia, respectively, operated by different groups. Assuming comparison between the two sets of data is technically permissible, the weight of plant material produced from the two-year-old stumps after two years of regrowth is estimated to be about fifty percent greater than from the one-year-old stumps, also after two years of regrowth.

Limited data on regrowth from cottonwood stands first harvested when they were two and six years old do not indicate any difference in yield after one year of regrowth from the stumps[48].

As a precaution when making projections of the range in annual average sustained yield expected from particular site-species combinations, yields from harvest schedules wherein the first harvest is taken from one and from two-year-old stands will be considered. Analyses similar to the one discussed in section V.B.3. of this appendix indicate that maximum sustained yields from harvest schedules which include a total of six harvests per planting starting with a first harvest from two-year-old stands are characteristically about ten percent smaller than when the first harvest is from one-year-old stands.

Number of harvests taken from a stand after the first harvest. Equation C-57 indicates that the effect of the number of harvests taken from a stand after the first harvest depends on the relationship between the yield from the first harvest and the yields from each of the subsequent harvests. If all the harvest yields were alike, which the experimental data for deciduous species indicate definitely not to be the case, even if equal values for n_1 and n_2 are chosen, the average annual sustained yield would be unaffected by the total number of harvests taken from a stand. Therefore, since Energy Plantations would always be operated on a harvest schedule which approximately maximizes the average annual sustained yield of plant material (that is, advantage will be taken of the increased yields from the first few harvests following the first harvest), the number of harvests which can be taken after the first harvest without impairing the average annual sustained yield is an important question (see Figure C-XXXVI, for instance).

Data shedding light on this question are few. In one case[29], four harvests after the first have been taken from sycamore stands, and the yields from these harvests varied in conformity with reasonable interpretation of the effect of the local weather during the period of years in which the harvests were taken. No other quantitative data on this point have been found, but it is the opinion of those consulted (the authors of references 1, 14, 16, 23 and 26, for instance) that at least five and possibly as many as seven or eight harvests can be taken from a healthy stand which is well adapted to its locale without noticeably impairing the yield per harvest subsequent to the first harvest. The selection of five harvests does not appear, therefore, to introduce any reasonable possibility for an error greater than one or two percent in the projected average annual sustained yields upon which the conclusions of this present work are based. As will be shown however in Appendix F, considerable cost advantage would accrue if as many as seven harvests after the first can be taken without impairing the yield per harvest after the first.

Harvestable Yields per Plant. It has been shown in section IV.B. of this appendix that the harvestable yield per plant from deciduous species at planting densities and with harvest schedules of interest for Energy Plantations can be represented by

$$y_n = \frac{K_1}{2K_2}\left(1 - e^{-K_2 n^2}\right) \qquad \text{(C-8)}$$

When this equation is used to describe the harvestable yield from the first harvest, n is the age of the stand at first harvest. When it is used for harvests subsequent to the first, n is the interval between the present and the preceding harvest.

It has been shown in section IV.B. of this appendix, on the basis of experimental data, that the parameters K can be related to the planting area A per plant by equations of the following forms:

$$K_1 = \mu_1 A^{\mu_2} \qquad \text{(C-17)}$$

$$K_2 = \eta_1 A^{\eta_2} \qquad \text{(C-23)}$$

$$\frac{K_1}{2K_2} = \gamma_1 A^{\gamma_2} \qquad \text{(C-26)}$$

The values of the parameters represented by the Greek letters in the equations for K_1 and K_2 seem to depend on several factors, among which are species, cultivation and fertilization at the plantation site, soil character and climate at the plantation site and on whether the harvest is the first from the stand or one of the first few subsequent to the first one. The values, therefore, appear to vary considerably between site and species (see Tables C-IX, C-X, C-XII and C-XIII). Moreover, the values estimated for these parameters are, at best, only approximate because they are based on very few data, some of which are for situations described only in rather general terms (for instance, "fertilized" but without any indication of fertilizer material content of the soil at the site prior to fertilization). Furthermore, many of the data have been collected within the most recent ten years or so and are therefore possibly affected in an unknown way by variations in the weather during that time. Until considerably more data have been collected from several plantings started at various times during two or three decades, the effect of weather on the parameter estimates cannot be discerned.

However, despite these difficulties with the data, the following tentative conclusions about the parameters have been reached:

- with respect to μ_1 - for first harvests from stands of a variety of species, the value of this parameter appears to range from about 0.15 to 0.4, and for second and subsequent harvests, from about 0.25 to about 0.7--errors in the value chosen for this parameter reflect themselves directly in similar fractional errors in estimated yields per plant;
- with respect to μ_2 - the values for this parameter appear to be relatively insensitive to all factors (including species well adapted to the growing site) except whether the first or a subsequent harvest is being considered--for first harvests its value appears to be about 0.7, and for subsequent harvests about 0.9 (see Tables C-IX and C-X)--a minus or plus twenty percent error in selecting this parameter will lead to an error of between about minus five and plus thirty percent, respectively, in estimated yields per plant for first harvests, and for harvests after the first, to an error of about plus and minus twenty percent;

- with respect to η_1 - values of this parameter appear to range from about 0.03 to 0.07 for first harvests and from about 0.2 to 0.5 for subsequent harvests (see tables C-XII and C-XIII)--a plus or minus twenty percent error in selecting this parameter will lead to an error of about plus or minus twenty percent in estimated yields per plant for first harvests, and for harvests after the first, to an error of about plus or minus fifteen percent; and
- with respect to η_2 - values of this parameter appear to range from about minus 0.1 to minus 0.5 for first and subsequent harvests--a plus or minus twenty percent error in selecting this parameter will lead to an error of about plus or minus eight percent in estimated yields per plant for first harvests, and for harvests after the first, to an error of about plus or minus five percent.

Theoretically, the ratio $K_1/2K_2$ is not an independent factor if values for K_1 and K_2 are available, and neither is equation C-26 if the parameters for equations C-17 and C-23 are known. However, because of the uncertainties in the yield data available, and consequently in the estimates of K_1 and K_2 and of the parameters in equations C-17 and C-23, an independent analysis has been made of the ratio $K_1/2K_2$ and the parameters in equation C-26. The analysis indicates that values for the parameter γ_1 extend over approximately the same ranges for first and subsequent harvests from all species for which data are available, the range for first harvests being from about one to 6.4 and for subsequent harvests from about 0.3 to 3.4. The ranges in values for γ_2 for first and subsequent harvests also seem to be about the same, namely from about 0.7 to 1.3 for first harvests and from about 0.5 to 1.2 for subsequent harvests.

Moreover, there is fairly convincing experimental evidence, partially supported by theoretical considerations, that the relation between the ratio $K_1/2K_2$ and the planting area A per plant may be fairly uniform for first and subsequent harvests for numerous deciduous species grown with cultivation, but not fertilization, at sites to which the species are well adapted (see section IV.B.8.a.). Some of the experimental data also suggest that the same may be true for at least several deciduous species grown at sites which are cultivated and fertilized.

In the light of these tentative findings, the sensitivity analysis has been limited to consideration of the $K_1/2K_2$ ratio itself as a function of planting area A per plant,and no consideration is given to the parameters in equation C-26. On this basis, errors in selecting values for the ratio when it is used with an independently determined value of K_2 for estimating harvestable yields per plant will lead to similar fractional errors in the yield estimates. When the ratio is used with an independently determined value of K_1 for estimating harvestable yields per plant, errors in the estimates for first harvests will be less than five percent and less than ten percent for subsequent harvests.

Effect of Errors in Harvestable Yield per Plant on Average Annual Sustained Yield. Because the yield per plant from the first harvest at planting densities and harvest schedules of practical interest for Energy Plantations is generally only a tenth to a third of the yield per plant from subsequent harvests, errors as large as fifty percent in the estimates for the first harvest when it is followed by five subsequent harvests will lead to an error of less than five percent in the estimate of the average annual sustained yield. However, errors in the estimates of yield from harvests subsequent to the first will reflect themselves as essentially the same fractional error in the average annual sustained yield.

VI.C. Conclusions and Preferred Choice of Parameters for Optimization. The sensitivity analysis is summarized in Table C-XXVII where it becomes

TABLE C-XXVII

SUMMARY OF SENSITIVITY OF AVERAGE ANNUAL SUSTAINED YIELD ESTIMATED (EQUATION C-57) TO VARIATIONS IN VALUES USED FOR PARAMETERS ESTIMATED FROM EXPERIMENTAL DATA

Parameter (and Equations)	Effects of ± 20% Variation (or as indicated) in Parameters on Primary Variables in Equation C-57: Primary Variable	Effect	Impact on Average Annual Sustained Yield Estimate, $\overline{Y}_n$	Other Consequences or Parameter Error
α (C-3+C-2):				
Cultivated Stands	N_n	< ± 5% in 3-yr-old stands	$\overline{Y}_n$ varies directly with N_{n_1}	-
Cult. & Fert. Stands	N_{n_1}	< ±15% in 3-yr-old stands	$\overline{Y}_n$ varies directly with N_{n_1}	-
β (C-3 + C-2):				
Cultivated Stands	N_{n_1}	< ± 3% in 3-yr-old stands	$\overline{Y}_n$ varies directly with N_{n_1}	-
Cult. & Fert. Stands	N_{n_1}	< ±12% in 3-yr-old stands	$\overline{Y}_n$ varies directly with N_{n_1}	-
N_{n_2}, N_{n_3}, ...	Experimental data suggest $N_{n_2} \approx N_{n_3}, \ldots \approx N_{n_1}$			
Stand age at 1st harvest	-	- - - -	$\overline{Y}_n$ with 1st harvest at age 1 year, approximately 10% larger than if at age 2 yrs.	Affects planting density and harvest schedule for maximum sustained Yield.
Number of harvests after the first	4 or 6 instead of 5		$\overline{Y}_n$ affected ± 2%	-
μ_1 (C-17):				
first harvests	y_{n_1}	± 20%	$\overline{Y}_n$ affected < ± 2%	Affects species selection, planting density & harvest schedule for maximum sustained yield.
subsequent harvests	y_{n_2}	± 20%	$\overline{Y}_n$ affected ± 20%	
μ_2 (C-17):				
first harvests	y_{n_1}	-5 to +30% (approx.)	$\overline{Y}_n$ affected < ± 2%	ditto
subsequent harvests	y_{n_2}	±20%	$\overline{Y}_n$ affected ± 20%	
n_1 (C-23):				
first harvests	y_{n_1}	± 20%	$\overline{Y}_n$ affected < ± 2%	ditto
subsequent harvests	y_{n_2}	± 15%	$\overline{Y}_n$ affected ± 15%	

TABLE C-XXVII (continued)

SUMMARY OF SENSITIVITY OF AVERAGE ANNUAL SUSTAINED YIELD ESTIMATED (EQUATION C-57) TO VARIATIONS IN VALUES USED FOR PARAMETERS ESTIMATED FROM EXPERIMENTAL DATA

Parameter (and Equations)	Effects of ± 20% Variation (or as indicated) in Parameters on Primary Variables in Equation C-57: Primary Variable	Effect	Impact on Average Annual Sustained Yield Estimated, $\overline{Y}_n$	Other Consequences or Parameter Error
n_2 (C-23):				
first harvests	y_{n_1}	±8%	$\overline{Y}_n$ essentially unaffected	ditto
subsequent harvests	y_{n_2}	±5%	$\overline{Y}_n$ affected ± 5%	
$K_1/2K_2$ (C-8):				
used with K_2				
1st harvests	y_{n_1}	±20%	$\overline{Y}_n$ affected <±2%	Affects planting density & harvest schedule for maximum sustained yield & possibly also species selection
subsequent harvests	y_{n_2}	±20%	$\overline{Y}_n$ affected ±20%	
used with K_1				
1st harvests	y_{n_1}	<±5%	$\overline{Y}_n$ essentially unaffected	
subsequent harvests	y_{n_2}	<±10%	$\overline{Y}_n$ affected <±10%	

clearly evident that the major sources for error in estimating average annual sustained yields arise from uncertainties in the estimates of

- the μ parameters in equation C-17 for estimating K_1 for harvests after the first from a stand,
- the value for $K_1/2K_2$ when used with K_2 in equation C-8 for estimating yields per plant from harvests after the first, and
- the parameter η_1 in equation C-23 for estimating K_2 for harvests after the first.

The estimates of the parameters α and β in equation C-3 for estimating the decay factor for determining plant survival rates in equation C-2 for plantations which are cultivated and fertilized,appear in the table to be potential sources of notable uncertainty. However, in actual plantation practice,such is not likely to be the case because fertilizing materials (largely spent sludge from synthetic-natural-gas production or ash from plant material used as solid fuel) will be returned to the land in the plantation after each harvest in order to maintain the productivity of the land at a reasonably steady level. As a consequence, it probably will not be necessary to apply fertilizing materials to newly planted areas until the young plants have established themselves, as for example in the year following the planting.

Because the ratio $K_1/2K_2$ appears to be widely independent of species whether first or subsequent harvests are being considered, it is a preferred parameter for estimating maximum average annual sustained yields. The parameter K_2 is preferred over K_1 for the second parameter because of the effect of uncertainties in the values of the μ parameters in equation C-17 for the parameter K_1.

VII. NUTRIENT BALANCE IN A DECIDUOUS-SPECIES PLANTATION

VII.A. Introduction and Summary Conclusion. Growing plants remove nutrients from the soil, and these nutrients are carried away with the plant material when it is harvested. Thus, unless nutrients are returned to the soil, repeated harvests gradually reduce the nutrient supply available in the soil for future plant growth. The rate at which the nutrient supply is depleted varies approximately directly with the rate at which plant material is grown and harvested. Maintaining the nutrient supply is, therefore, an important consideration in Energy Plantation operation. The nutrients of most concern are fixed nitrogen, phosphates and potassium salts. The minor nutrients, which include iron, zinc, manganese, iodine, sulphur and a few others, are generally available in sufficient amounts in soils so that their regular replenishment is rarely a matter of continuing concern.

It is concluded that, if the plant material produced in the plantation is used for synthetic natural gas, and if the spent sludge from the gas production facility is returned to the plantation, the nutrient supply at the plantation will be maintained at a satisfactory level. However, if the produce of the Energy Plantation is consumed as solid fuel, returning the ash to the plantation will maintain only the phosphate and potassium salt levels at the plantation--the fixed-nitrogen requirement will have to be met by other means. It is assumed that whatever nutrient deficiencies may have existed at the plantation site when it began to be used as an Energy Plantation will have been made up with conventional fertilizer material at that time.

VII.B. Nutrient Removal at Harvest. The data available[27,49]. on nutrients in plant material harvested from deciduous species grown in dense plantings are summarized in Table C-XXVIII.

It is apparent that the fixed nitrogen removed at harvest, expressed as pounds of fixed nitrogen per dry ton harvested, is reasonably constant for the five cases grown in Maine, and is essentially independent of species and age at harvest. The average value of nitrogen removed for the five Maine cases is identical with that recorded for sycamore grown in Georgia. In the latter case, the harvested material was generated from stumps which had already been harvested once. It can thus be stated with reasonable certainty that about six pounds of fixed nitrogen are removed from the site at harvest for each dry ton harvested, and that the removal rate is essentially independent of the species, the planting density, the location and the age of the plant matter at harvest. The data for phosphorus and potassium are not as homogeneous as the nitrogen data, but still strongly suggest that about 0.80 pound of phosphorus and about 3.25 pounds of potassium are removed from the site for each oven-dry ton harvested.

VII.C. Nutrient Balance for Short-Rotation Plantations. The residues remaining from the harvested plant material after it has been used for fuel will be returned to the plantation site for convenient disposition and for its fertilizer value.

If the plant material is used as a solid fuel, substantially all the ash produced (about twenty pounds per oven-dry ton of plant material burned) will be recovered either from under the firebox grate or from the precipitator or other particulates control device on the firebox stack. The ash will contain essentially all the phosphate, potassium, and trace metals carried away from the plantation in the harvested plant material.

TABLE C-XXVIII

NUTRIENTS IN PLANT MATERIAL HARVESTED FROM DECIDUOUS SPECIES

Species	Age at Harvest	Pound of Nutrient Per Dry Ton Harvested			Location and Reference
		Nitrogen	Phosphorus	Potassium	
Red Maple	18	8.86	1.27	4.64	Maine, Reference 27.
Red Maple	30	6.68	1.00	3.79	
Quaking Aspen	45	6.72	0.62	3.23	
Paper Birch	39	5.07	0.60	2.54	
Paper Birch	29	5.96	0.80	3.76	
Average	-	6.15	0.86	3.59	
Sycamore(1)	2	6.16	0.77	2.91	Georgia, Reference 49.

(1) Second-harvest data.

By returning the ash to the land in the plantation, the level of these plant nutrients in the land will be maintained, thereby helping to assure the continued high productivity of the plantation site. None of the fixed nitrogen carried away from the plantation in the harvested plant material is expected to find its way into the ash. In fact, it will be lost, primarily as elemental nitrogen, in the flue gas from the firebox. When plant material from Energy Plantations is used as a solid fuel, it will be necessary to fertilize the plantation site with fixed nitrogen at a rate of approximately six pounds of nitrogen per dry ton harvested. If the plant material is used for synthetic-natural-gas production, the spent sludge taken from the anaerobic digester will contain essentially all the plant nutrients, including most of the fixed nitrogen, carried away from the plantation in the harvested plant material. Moreover, in preparing the slurry containing the plant material from the Energy Plantation which is fed to the anaerobic digesters in the SNG production facility, fixed nitrogen is added to the slurry to adjust the fixed-nitrogen-to-carbon ratio to that required for good biological digestion. The amount of fixed nitrogen so required is estimated in Appendix D. But between the amount added and that brought in with the plant material, the spent sludge from the anaerobic digester returned to the plantation is estimated to contain about eighteen-pounds of fixed nitrogen per ton of plant material processed and hence harvested. This amount of fixed nitrogen returned to the plantation is more than enough to meet the nitrogen fertilizer requirements.

VII.D. Conclusions. The amounts of plant nutrients, and particularly of fixed nitrogen, removed from a plantation site when harvesting plant matter are directly proportional to the amount of plant matter removed. The nutrients removed per dry ton of material harvested appear to be essentially constant, irrespective of the species grown, the location and climate, the age of the plants at harvest, the planting density and the fact that the plant matter harvested results from first growth or from a growth subsequent to a first harvest.

If plant material from the plantation is used directly as a solid fuel, the fixed-nitrogen fertilizer requirement at the plantation will have to be supplied by fertilizer or other means, but returning the ash produced by combustion of the plant material to the plantation will satisfy all the other fertilizer and trace-element requirements.

If the plant material is used for making synthetic natural gas, and if the spent sludge from the digester is returned to the plantation, no outside sources of fertilizer will be required at the plantation.

VIII. OPTIMIZATION ESTIMATES FOR SPECIFIC SPECIES

VIII.A. Introduction and Summary. It will be shown in Appendices F and G that the most promising deciduous species for plantations at Forts Benning and Leonard Wood include hybrid poplars, eastern cottonwood (*P. deltoides*), Missouri cottonwood, Sioux male cottonwood, silver maple, and sycamore. Other species have been ruled from consideration, because their inherent growth rates are too slow or because their climate preferences probably make them unsuitable for the locales of Forts Benning or Leonard Wood. A few species could not be given consideration because insufficient growth data are available for them. Among the species ruled out for one or more of these three reasons are aspen, black cottonwood, red alder and quaking aspen.

In this subsection of the appendix, estimates are made of the planting densities and harvest schedules which are expected to produce the highest sustained annual yields in each of three circumstances at the sites for which growth data are available from species believed to be specially attractive for plantations at Forts Benning and Leonard Wood. These "highest-yield estimates" will be used in Appendices F and G in conjunction with the procedures described in section IV.B.9. for allowing for the effect of local climate at Benning and Leonard Wood on the sustained yields from the preferred species. The three circumstances for which the sustained yield estimates are made are:

- the highest sustained yield expected from stands in which the planting area A per plant if four square feet or more,
- the second highest estimated sustained yields under the conditions described in the preceding point, and
- the highest yield expected from stands whose planting area per plant is four square feet or more and the first harvest is taken from the stand when it is at least two years old.

These three sets of estimates suggest that sustained yields between about seven and ten dry tons of plant material per acre per year can reasonably be expected from the species analyzed, at the sites at which the data for them was collected. Twelve of the fourteen highest yield estimates are at planting areas per plant of four square feet with the first harvest being taken when the stands are one year old. The other two high estimates are at a variety of planting areas and harvest schedules.

<u>VIII.B. Optimization Calculations for Deciduous Species</u>. The planting densities and harvest schedules which can be expected to produce each of the three highest sustained yield estimates were made in accord with the procedure described in section V.B. The estimates are summarized in Table C-XXIX. In every case, except the estimates for hybrid poplar from Clone 49, the sustained yield estimates are based on estimates of the parameters $K_1/2K_2$ and K_2 derived as a function of planting area A per plant from equations C-26 and C-23, respectively, or equations derived from these equations. In the case of poplar from Clone 49, the yield estimates are based on estimates of the parameters $K_1/2K_2$ and K_1 as a function of A based on equations C-26 and C-17. It was assumed for making the estimates of $K_1/2K_2$ as a function of A in all cases that the same relationship applies to the first harvest and subsequent harvests (see page C-110).

More specific comments about the input data used for the estimates for each species follow.

<u>Hybrid Poplar - Clone NE-388 - Musser Farm, Pa.</u>

$K_1/2K_2$ - equation C-28 - $\gamma_1 = 1.326$, $\gamma_2 = 1.061$.
K_2 - first harvest - Table C-XII - $\eta_1 = 0.0346$, $\eta_2 = -0.223$
-second harvest - Table C-XIII - $\eta_1 = 0.431$, $\eta_2 = -0.302$

ESTIMATED PLANTING DENSITIES AND HARVEST SCHEDULES EXPECTED TO PRODUCE HIGH SUSTAINED YIELDS FROM VARIOUS SPECIES GROWN AT THE SITES FROM WHICH THEIR GROWTH DATA WERE COLLECTED

(see section VIII.B. for the basis of the individual estimates)

Species	Site	Reference	High Yield Category[1]	Planting Area Ft^2 Per Plant	Harvest Schedule[2]	Estimated Sustained Yield Dry Tons Per Acre-Year
Hybrid Poplar:						
-NE-388	Musser Farm, Pa.	1	Highest	4	1-2	9.43
			2nd highest	6	1-2	9.08
			Highest-$n_1>1$ Yr.	4	2-2	8.52
-NE-388	Stone Valley, Pa.	17	Highest	4	1-2	9.80
			2nd highest	6	1-2	8.72
			Highest-$n_1>1$ Yr.	4	2-2	8.96
-49	Stone Valley, Pa.	17	Highest	4	1-4	9.13
			2nd highest	4	1-3	8.87
			Highest-$n_1>1$ Yr.	4	2-4	8.50
-252	Stone Valley, Pa.	17	Highest	4	1-2	7.86
			2nd highest	6	1-2	6.94
			Highest-$n_1>1$ Yr.	4	2-2	7.20
Cottonwood ("high" values)	Mississippi	10	Highest	4	1-3	13.80
			2nd highest	4	1-2	13.16
			Highest-$n_1>1$ Yr.	4	2-3	11.35
("low" values)	Mississippi	10	Highest	4	1-3	9.20
			2nd highest	4	1-2	8.78
			Highest-$n_1>1$ Yr.	4	2-3	7.57

TABLE C-XXIX (continued)

ESTIMATED PLANTING DENSITIES AND HARVEST SCHEDULES EXPECTED TO PRODUCE HIGH SUSTAINED YIELDS FROM VARIOUS SPECIES GROWN AT THE SITES FROM WHICH THEIR GROWTH DATA WERE COLLECTED

(see section VIII.B. for the basis of the individual estimates)

Species	Site	Reference	High Yield Category[1]	Planting Area Ft^2 Per Plant	Harvest Schedule[2]	Estimated Sustained Yield Dry Tons Per Acre-Year
Missouri Cottonwood	Tuttle, Kansas	14	Highest	14	1-3	11.12
			2nd highest	16	1-3	11.10
			Highest-n_1>1 Yr.	16	2-3	10.25
	Milford, Kansas	14	Highest	4	1-2	11.07
			2nd highest	6	1-3	10.51
			Highest-n_1>1 Yr.	4	2-2	9.70
Sioux Male Cottonwood	Tuttle, Kansas	14	Highest	4	1-2	13.68
			2nd highest	14	1-3	13.48
			Highest-n_1>1 Yr.	14	2-3	12.91
	Milford, Kansas	14	Highest	4	1-2	14.83
			2nd highest	6	1-2	14.22
			Highest-n_1>1 Yr.	6	2-2	13.35
Silver Maple	Tuttle, Kansas	14	Highest	16	1-4	7.09
			2nd highest	18	1-4	7.07
			Highest-n_1>1 Yr.	16	2-4	6.70
	Milford, Kansas	14	Highest	4	1-3	7.42
			2nd highest	6	1-4	7.24
			Highest-n_1>1 Yr.	4	2-3	6.82

TABLE C-XXIX (continued)

ESTIMATED PLANTING DENSITIES AND HARVEST SCHEDULES EXPECTED TO PRODUCE HIGH SUSTAINED YIELDS

FROM VARIOUS SPECIES GROWN AT THE SITES FROM WHICH THEIR GROWTH DATA WERE COLLECTED

(see section VIIII.B. for the basis of the individual estimates)

Species	Site	Reference	High Yield Category[1]	Planting Area Ft^2 Per Plant	Harvest Schedule[2]	Estimated Sustained Yield Dry Tons Per Acre-Year
Sycamore ("high" values)	Georgia	29	Highest	4	1-3	11.55
			2nd highest	6	1-3	11.47
			Highest-η_1>1 Yr.	8	2-3	10.10
("low" values)	Georgia	29	Highest	20	1-3	5.89
			2nd highest	18	1-3	5.83
			Highest-η_1>1 Yr.	20	2-3	5.45

Note 1: Highest = highest estimated sustained annual yield from stands with planting area per plant equal to four square feet or more.
2nd highest = second highest estimated sustained yield under conditions described for "highest" yield.
Highest-η_1>1 Yr. = highest yield from stands meeting requirements for "highest" yield, except first harvest is not taken before stand is two years old.

Note 2: The two numbers in this column indicate the age in years of the stand at first harvest followed by the interval in years between subsequent harvests.

Hybrid Poplar - Clone NE-388 - Stone Valley, Pa.

$K_1/2K_2$ - Table C-XIV - $\gamma_1 = 1.603$, $\gamma_2 = 0.893$.
K_2 - first harvest - Table C-XII - $\eta_1 = 0.0577$, $\eta_2 = -0.200$.
second harvest - from equation C-24.

Hybrid Poplar - Clone 49 - Stone Valley, Pa.

$K_1/2K_2$ - Table C-XIV - $\gamma_1 = 3.590$, $\gamma_2 = 0.678$.
K_1 - first harvest - Table C-IX - $\mu_1 = 0.510$, $\mu_2 = 0.398$
second harvest - from equation C-21.

Hybrid Poplar - Clone 252 - Stone Valley, Pa.

$K_1/2K_2$ - Table C-XIV - $\gamma_1 = 1.465$, $\gamma_2 = 0.727$.
K_2 - first harvest - Table C-XII - $\eta_1 = 0.502$, $\eta_2 = +0.0592$
second harvest - from equation C-24.

Eastern Cottonwood (*P. deltoides*) - Mississippi

$K_1/2K_2$ - when the value for γ_1 shown in Table C-XIV (6.438) is used for estimating $K_1/2K_2$, estimated yields from the species reach about thirty dry tons per acre-year, which is unrealistic--two values for γ_1 have been chosen:

"high" value - the approximate average of γ_1 (6.438) for cottonwood and γ_1 (0.984) for "cottonwood and hybrid poplar-unfertilized" in Table C-XIV, and

"low" value - about equal to the average of the value of γ_1 for the four hybrid poplar clones.

The value for γ_2 (0.961) is taken from Table C-XIV .

K_2 - first harvest - Table C-XII - η_1 = 0.0416, η_2 = -0.349
second harvest - value of K_2 for first harvests multiplied by the ratios of K_2 for first and second harvests from equation C-24.

Missouri Cottonwood - Tuttle, Kansas

$K_1/2K_2$ - Table C-XXIV - γ_1 = 1.182, γ_2 = 1.278.

K_2 - first harvest - Table C-XXIV - η_1 = 0.0568, η_2 = -0.331
second harvest - value of K_2 for first harvests multiplied by the ratios of K_2 for first and second harvests from equation C-24.

Missouri Cottonwood - Milford, Kansas

$K_1/2K_2$ - Table C-XXIV - γ_1 = 1.360, γ_2 = 1.190.

K_2 - first harvest - Table C-XXIV - η_1 = 0.0726, η_2 = -0.488
second harvest - same procedure as for Tuttle, Kansas

Sioux Male Cottonwood - Tuttle, Kansas

$K_1/2K_2$ - Table C-XXIV - γ_1 = 1.295, γ_2 = 1.265.

K_2 - first harvest - Table C-XXIV - η_1 = 0.715, η_2 = -0.374
second harvest - same procedure as for Missouri Cottonwood at Tuttle, Kansas.

Sioux Male Cottonwood - Milford, Kansas

$K_1/2K_2$ - Table C-XXIV - γ_1 = 1.436, γ_2 = 1.222

K_2 - first harvest - Table C-XXIV - η_1 = 0.0952, η_2 = -0.491.
-second harvest - same procedure as for Sioux Male Cottonwood at Tuttle, Kansas.

Silver Maple - Tuttle, Kansas

$K_1/2K_2$ - Table C-XXIV - regression analysis of the values for first and second harvests for γ_1 and γ_2, respectively, - $\gamma_1 = 1.058$, $\gamma_2 = 1.218$.

K_2 - first harvest - Table C-XXIV - $\eta_1 = 0.0956$, $\eta_2 = -0.609$
second harvest - Table C-XXIV - $\eta_1 = 0.298$, $\eta_2 = -0.478$

Silver Maple - Milford, Kansas

$K_1/2K_2$ - Table C-XXIV - $\gamma_1 = 1.419$, $\gamma_2 = 1.124$.
K_2 - first harvest - Table C-XXIV - $\eta_1 = 0.0697$, $\eta_2 = -0.535$
second harvest - assumed values of K_2 for first and second harvests are in the same ratio as the corresponding value for silver maple at Tuttle, Kansas.

Sycamore

$K_1/2K_2$ - two cases are considered:
"high" value - the relationship between $K_1/2K_2$ and planting area A per plant was obtained by regression analysis of all values shown for the ratio in tables C-V and C-VII - $\gamma_1 = 2.563$ and $\gamma_2 = 0.954$ and
"low" value - the values for regrowth from fertilized two-year-old stumps (Table C-XV) - $\gamma_1 = 0.775$ and $\gamma_2 = 1.162$.

K_2 - first harvest - Table C-XII - "all plantings" values - $\eta_1 = 0.0724$ and $\eta_2 = -0.0403$.

second harvest - Table C-XIII - the values for regrowth from fertilized two-year-old stumps - $\eta_1 = 0.230$ and $\eta_2 = -0.174$.

The reasons for estimating the "low" value for $K_1/2K_2$ using the second harvest data from Table C-XV are that the data:

- are the most systematic available for sycamore, and
- are the only set for sycamore which show the expected decline of K_2 with increasing values of planting area A per plant.

VIII.C. Discussion of the Results. Each of the species or varieties considered in Table C-XXIX displays trends which merit comment. The following comments are based on Figures C-XXVII through C-XLII, which show the effect of variation in the planting area A per plant on the estimated average annual sustained yields.

- Hybrid Poplars

  Except for the case of clone 49, the optimum planting and harvesting cycle is four square feet per plant, one year growth before first harvest and two years of growth between the subsequent harvests. As is apparent in Figure C-XXXVII, the yields increase sharply at higher planting densities--the actual maximum yields being at planting areas less than four square feet per plant, which is the densest planting which can be conveniently handled by machinery in the field. For each of the clones, only the harvesting cycle leading to the maximum yield is plotted. The predicted maximum yields are in the range of 7.8 to 9.8 dry tons per acre-year. These values are comparable to, but slightly higher than those reported by the author[1,17] of the data on which the yield estimates are based. This difference is not surprising as the optimization assumed identical asymptotic yield curves ($K_1/2K_2$) for first and subsequent harvests, which, as discussed earlier, is reasonable if fertilization is included in the cultural practices. An interesting feature of the results of Table C-XXIX is that, in some cases, yields comparable to the maximum yields can be obtained at somewhat lower planting densities. For example, in the case of NE-388, at six square feet per plant and a 1-2 harvest, the estimated yield is 9.08 dry tons per acre-year compared with 9.43 at four square feet per plant and a 1-2 harvest cycle; this is a reduction of only about four percent in yield for a reduction of over thirty percent on the number of plants. A similar situation is observed for the same clone NE-388 at the other site. Both alternative points are indicated by open circles on the figure. The economic implications of these two alternatives will be examined in appendices F and G.

In most cases, switching from the optimum cycle which has a one year first growth period, to the highest yield cycle having a two year first growth period reduced the yields by about ten percent.

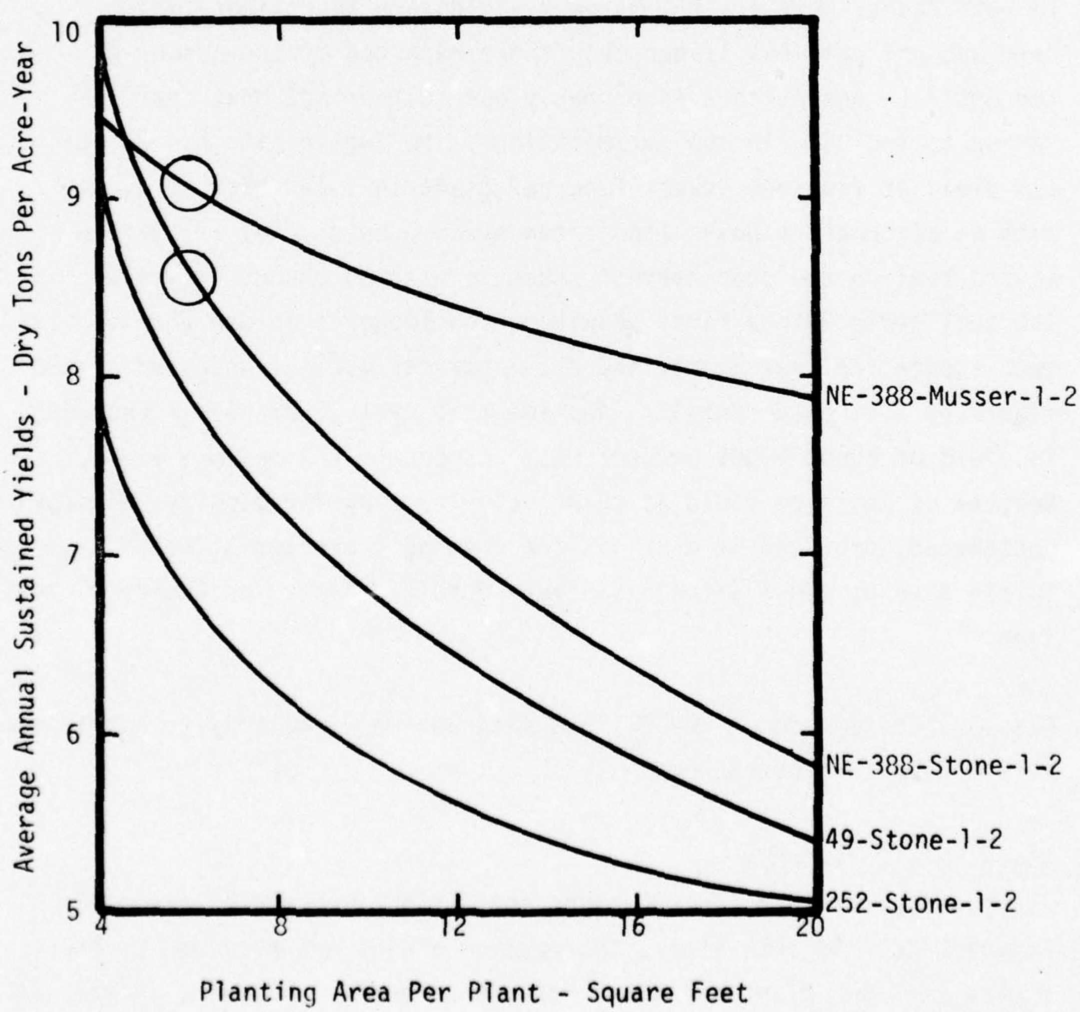
- Eastern Cottonwood

The high and low yield curves are plotted in Figure C-XXXVIII for the corresponding optimum harvest cycles (1-3). The maximum yields are in the range of 9 to 13.8 dry tons per acre-year. Most of the reported yields[10,27] are closer to the lower limit. A reduction in the number of plants by about thirty percent (from four square feet to six square feet per plant) leads to a reduction of about eight percent in the maximum average yields in both the "low" and "high" estimates. The six-square-feet points are indicated by open circles on the figure. The loss in yield caused by making the first harvest at two years old is of the order of seventeen percent in this case.

FIGURE C-XXXVII

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELD FROM VARIOUS HYBRID POPLARS

Harvest cycles indicated as x-y - where x is stand age at first harvest and y is interval between harvests



- Missouri Cottonwood

  The yield curves for the two Kansas locations are plotted on Figure C-XXXIX. The harvest cycles shown lead to the maximum yields. The differences in the shapes of the yield-versus-planting-area curves are related to differences in the values of the parameters used in the optimization process.

  In both cases, however, the maximum yields are approximately the same and are somewhat larger than those reported by the author of the data[14]. Again, this is probably due to the fact that fertilization is included in the optimization. The Tuttle site has an optimum yield at fourteen square feet per plant in a 1-3 harvest cycle, with an alternative point (indicated by an open circle) at sixteen square feet on the same harvest schedule with no change in yield. The best cycle with a first growth period longer than one year is sixteen square feet per plant, and a 2-3 harvest cycle (indicated on the figure by a circled cross). Adopting that cycle indicates a reduction in yield of about eight percent with respect to the maximum yield. Because of its high yield at relatively low planting density, Missouri Cottonwood, provided it displays the growing characteristics of the Tuttle site at other sites, is a very good candidate for Energy Plantation.

  Missouri Cottonwood at the Milford site behaves similarly to hybrid poplars and eastern cottonwood.

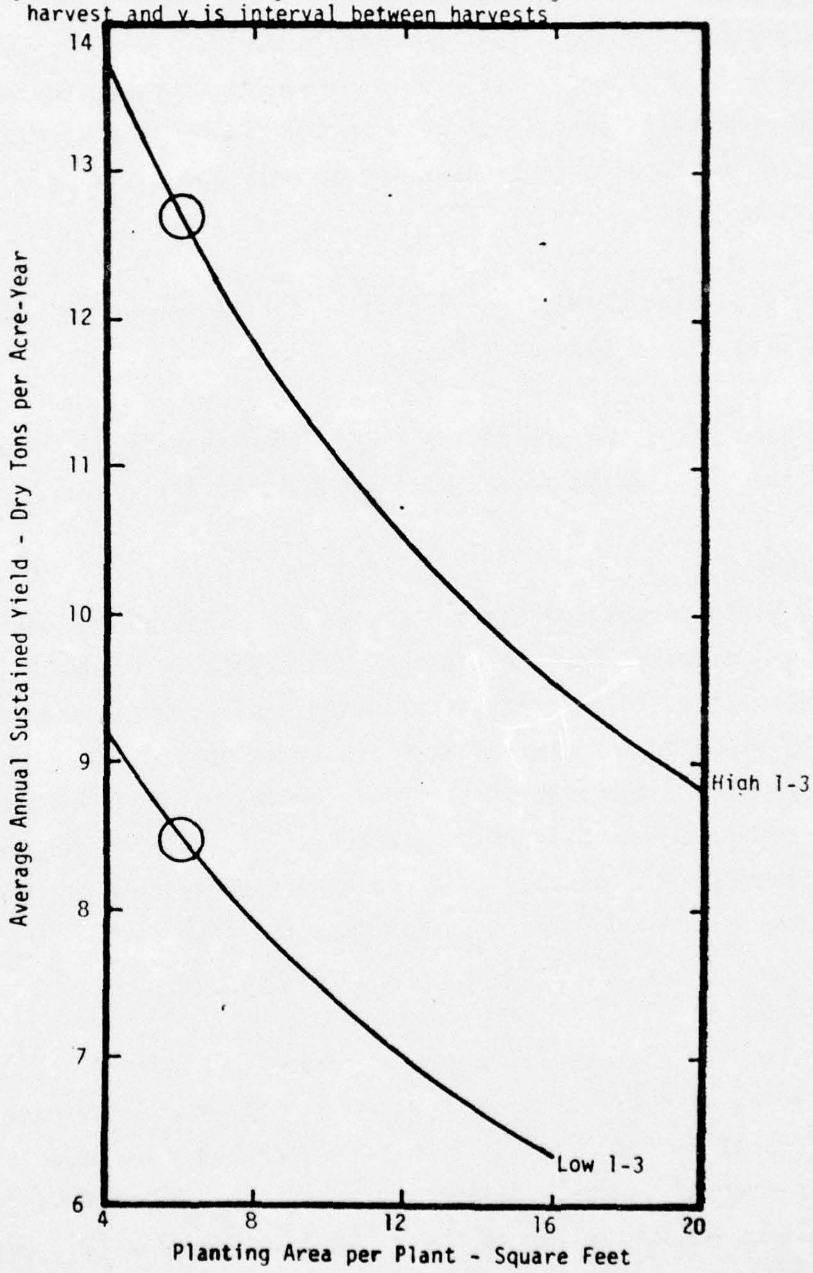
- Sioux Male Cottonwood

  The yield curves for the two sites and the optimum cycles are shown in Figure C-XL. At both sites, the maximum yields are provided by four square feet per plant and a 1-2 harvest schedule. However, in the case of the Tuttle site an alternative, second-best choice is at

FIGURE C-XXXVIII

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELD FROM COTTONWOOD (*P. deltoides*)

Harvest cycles indicated as x-y - where x is stand age at first harvest and y is interval between harvests



fourteen square feet and a 1-3 harvest cycle (indicated by an open circle in the figure)--reduction of seventy percent in the number of plants and change in the harvest cycle leading to a reduction of only about one and a half percent in yield. The best cycle with a two-year (or more) first growth period is fourteen square feet and a 2-3 harvest cycle (indicated in the figure by a circled cross), which corresponds to a reduction of only about six percent of the maximum yield.

The situation at Milford is similar to that described for hybrid poplars and eastern cottonwood.

At each site, the yields are larger than those reported by the author[14] of the data, which may be partly due to fertilization.

- Silver Maple

  The yield curves for the two Kansas sites follow the same patterns as those described for the Missouri cottonwood in Figure C-XLI. At the Tuttle site, an alternative planting density with essentially the same yield as the maximum is shown by an open circle, while a possible cycle with a two-year first growth period is shown by a circled cross. Prospects at the Milford site are similar to those for hybrid poplars and eastern cottonwood. The yields are comparable to those reported by the author[14] of the original data for both sites.

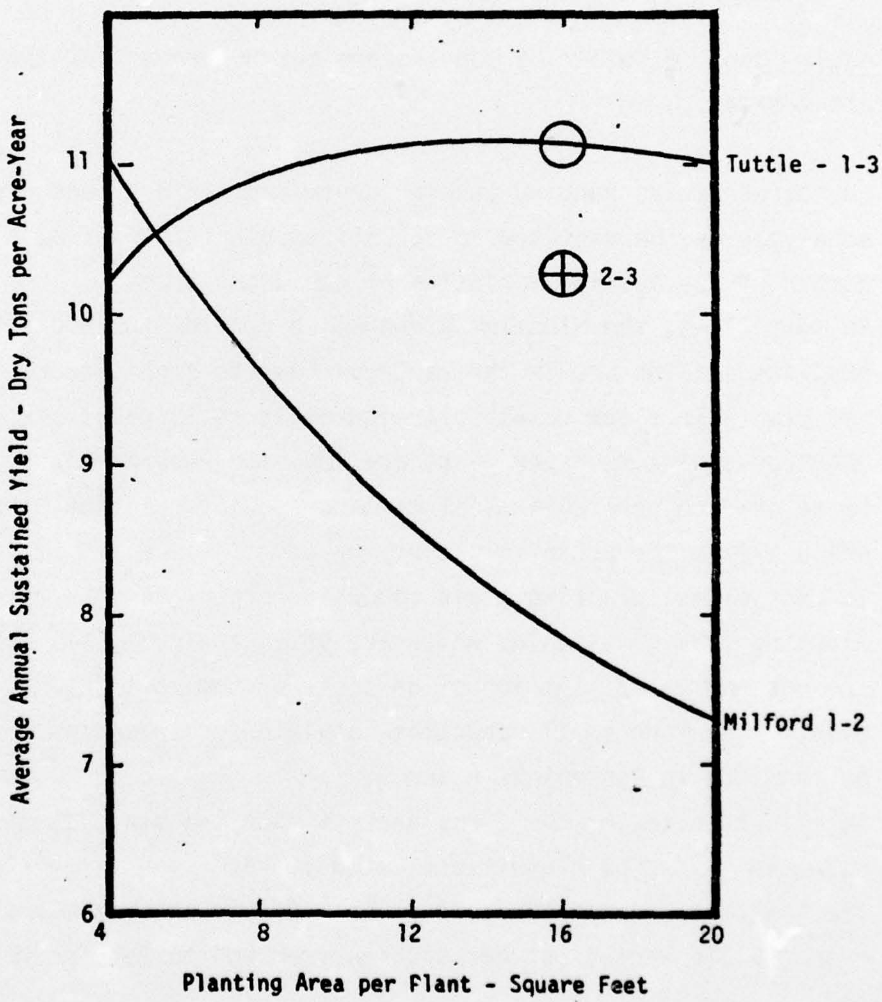
- Sycamore

  The low and high yield curves are shown in Figure C-XLII. The low yield curve does not seem to reach a maximum yield within the range of values of A considered in the figure, probably because of the scattered character of the original data (see Tables C-V and C-VII). The high yield curve is similar to those for hybrid poplar (although with longer

FIGURE C-XXXIX

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELD FROM MISSOURI COTTONWOOD

Harvest cycles indicated as x-y - where x is stand age at first harvest and y is interval between harvests



intervals between harvests to reach the maximum yield). An alternative choice of planting density is shown by an open circle, while a cycle with a two-year first growth period is indicated by a circled cross. The yield values reported in the literature (References 2, 16, 17 and 18) are generally between the two curves in Figure C-XLII.

VIII.D. Conclusions. A number of conclusions may be drawn from the optimization calculations:

- sustained yields ranging between seven and ten dry tons per acre-year may be expected in fertilized plantations from a number of species and varieties of deciduous trees;
- in most cases, the planting areas which provide the highest sustained yields are in the range of four to eight square feet per plant--in a few cases, planting areas as large as sixteen or eighteen square feet per plant are indicated--such cases may be related to particular soil-climate-species relationships which may not be achievable everywhere;
- in most cases, planting areas somewhat larger than the optimum planting area give yields which are only marginally smaller than the optimum yield--the impact on costs of the lower number of plants and often small reduction in yield for these cases will be examined in Appendices F and G;
- in all cases,taking the first harvest when the stand is one year old gives the highest estimated yield;
- the interval between harvests which leads to the maximum sustained yield varies between species from two to four years; and
- in some cases, it is possible to take the first harvest when the stand is two years old without suffering very much of a yield penalty--this practice should be encouraged whenever the penalty in yield is small.

FIGURE C-XL

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELDS FROM SIOUX MALE COTTONWOOD

Harvest cycles indicated as x-y - where x is stand age at first harvest and y is interval between harvests

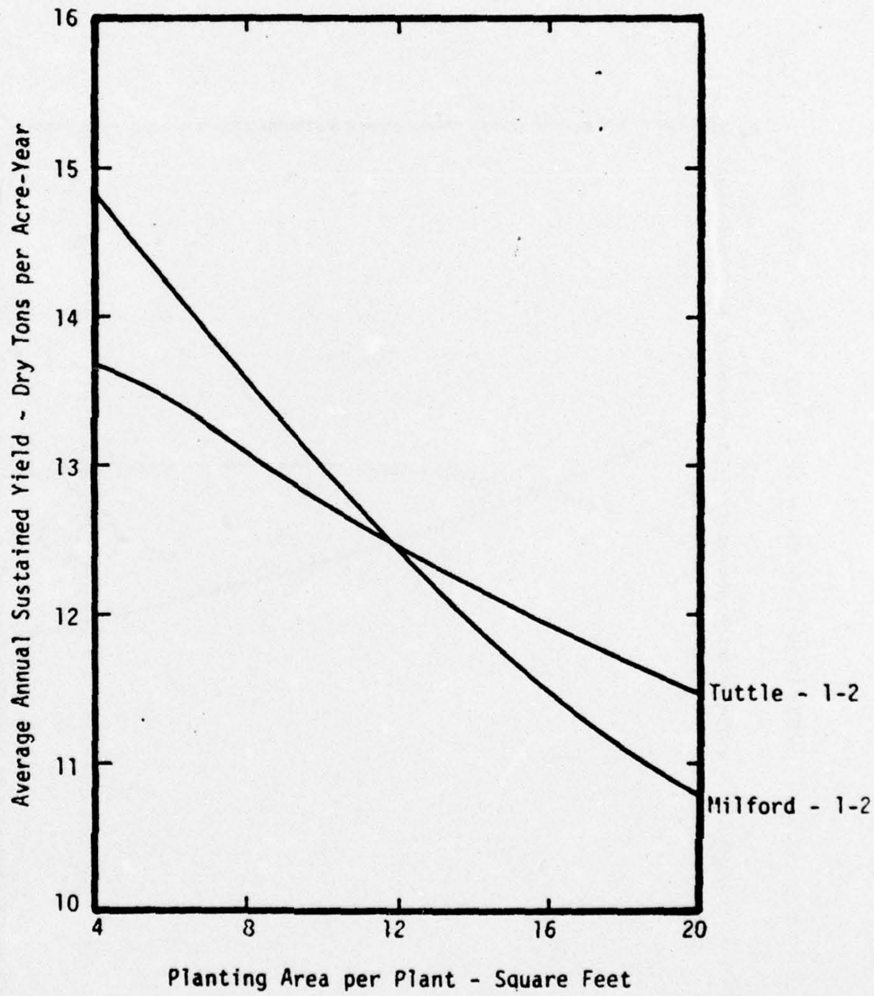


FIGURE C-XLI

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELDS FROM SILVER MAPLE

Harvest cycles indicated as x-y - where x is stand age at first harvest and y is interval between harvests

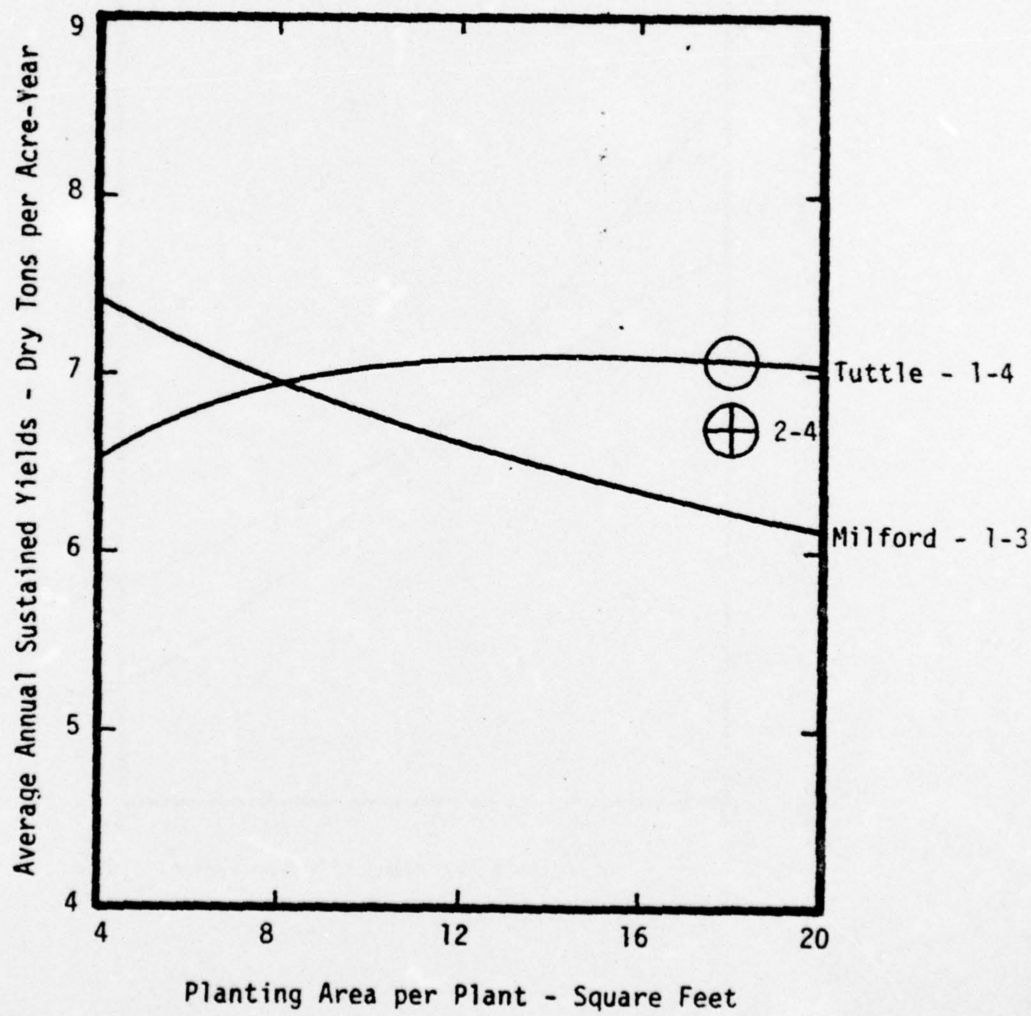
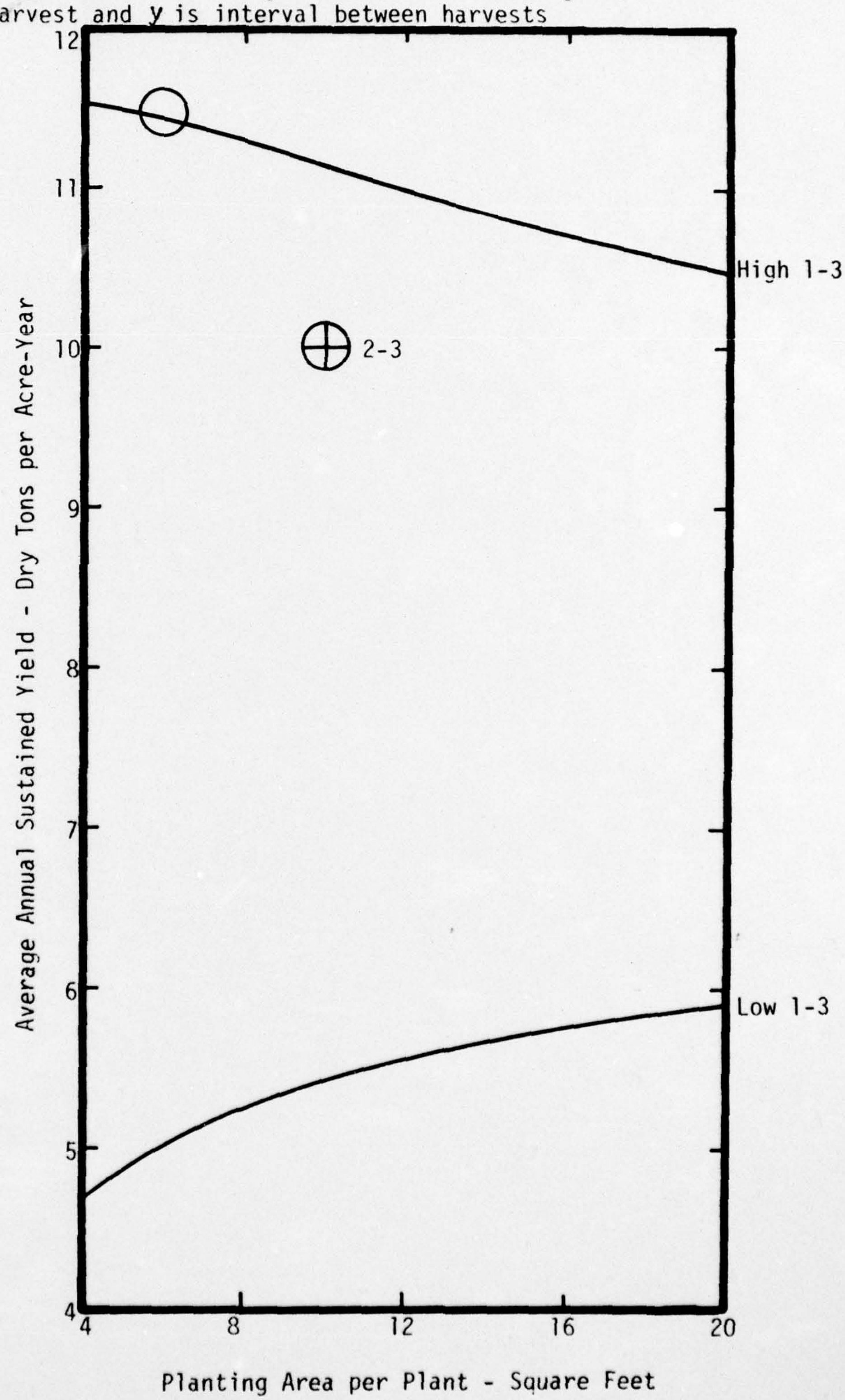


FIGURE C-XLII

ESTIMATED AVERAGE ANNUAL SUSTAINED YIELDS FROM SYCAMORE

Harvest cycles indicated as x-y - where x is stand age at first harvest and y is interval between harvests



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DEFINITION OF SYMBOLS

A Land area per plant at planting time in square feet (A is the reciprocal of N_o when the area of an acre is expressed in square feet).

a Decay parameter in equation C-2 having the dimension of the reciprocal of years.

d_i Number of days during which photosynthesis is expected to occur in a month in the growing season.

g See page C-48.

h_i The average number of hours of sunshine per day during the i^{th} month of the growing season.

I_i The average daily insolation during the i^{th} month expressed in Langleys.

K_1 Growth parameter in equation C-4 expressed in pounds per plant per year squared.

K_2 Growth-limiting parameter in equation C-4 expressed as a pure number per year squared.

k_1 Computer notation in equations C-9 through C-12 for K_2.

k_2 Computer notation in equations C-9 through C-12 for $K_1/2K_2$.

k(t) The fraction of the plant material photosynthesized which contributes to the accumulation of plant material above ground per plant.

L Total leaf area per plant.

Le Effective leaf area per plant, square decimeters.

m Number of harvests taken from a stand after the first harvest.

N Number of living plants per acre.

N_o Number of plants originally planted per acre.

N_n Number of plants surviving per acre from the original planting at year n.

N_{n_1} Number of plants surviving per acre from the original planting at the year n in which the first harvest is taken.

N_{n_2} Number of plants surviving per acre from the original planting at the time of the second harvest taken n years after the first harvest was taken (N_{n_3} has a comparable meaning for the third harvest, and N_{n_4}, for the fourth, and so on.).

n Age in years of the harvestable plant matter above the ground since planting if there has been no harvest from the planting, or the age of the plant matter since the immediately preceding harvest.

P(t) The total amount of plant material photosynthesized per plant up to time t.

R The rate of photosynthesis, milligrams of carbon dioxide assimilated per month per unit surface of effective leaf area.

Y_n The yield of harvestable plant material per acre at year n in pounds per acre.

$\overline{Y}_n$ Average annual sustained yield from a planting in a plantation over a total period of N years - tons of harvested plant material per acre per year.

y_n The average harvestable yield of plant material per plant at year n in dry pounds of plant material.

y_t The plant material above ground, pounds per plant at time t.

α A constant in equation C-3.

α_c A factor in equation C-32.

β The exponent in equation C-3--a pure number.

γ A factor in equation C-31.

γ_1 A constant in equation C-26.

γ_2 An exponent in equation C-26.

ε The fraction of the total leaf area which receives enough light to contribute significantly to the photosynthetic process.

η_1 A constant in equation C-23.

η_2 An exponent in equation C-23.

θ_i Temperature weight factor equal to $1-0.016\ (T-65)^2$ in equation C-35 where the temperature T is in Fahrenheit degrees.

λ_1 A constant in equation C-14.

λ_2 An exponent in equation C-14.

μ_1 A constant in equation C-17.

μ_2 An exponent in equation C-17.

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