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Net Financial and Energy Analyses for Producing Populus Hybrid Under Four Management Strategies First Rotation

June 1985

Paul R. Blankenhorn
Todd W. Bowersox
Charles H. Strauss
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Maria L. DiCola
Carole Hornicsar
Bruce E. Lord

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The Pennsylvania State University
School of Forest Resources
College of Agriculture
University Park, PA 16802

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Net Financial and Energy Analyses for Producing *Populus* Hybrid Under Four Management Strategies First Rotation

Final Report
June, 1985

by

Paul R. Blankenhorn, Todd W. Bowersox, Charles H. Strauss
Lee R. Stover, Stephen C. Grado, Gwen L. Stimely,
Maria L. DiCola, Carole Hornicsar and Bruce E. Lord

The Pennsylvania State University
School of Forest Resources
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ABSTRACT

Biomass yield and growth rate data for *Populus* hybrid grown under four management strategies on two dissimilar sites were obtained. Biomass production data, combined with fuel and chemical properties, were expanded into complete net financial and energy analyses in order to recommend a management/conversion strategy with the most favorable financial and energy considerations. To develop the necessary biomass production data, six replications were established under four management strategies (control, fertilization, irrigation and fertilization/irrigation) on two sites representing favorable (Basher site) and unfavorable (Morrison site) inherent growth conditions. Fertilization and irrigation amendments were applied to designated plots based upon detailed monitoring and determination of needed amendments.

Plantation operations were divided into two phases, establishment and maintenance. The various operations within each phase were analyzed to determine their financial costs and energy requirements. These analyses were based on the financial and energy cost per hectare to complete each operation in each of the phases for a conceptual sized commercial working unit. The engineering and time constraints imposed on each operation were analyzed. A maximum working unit of 924 ha was contingent upon the limits of the offset disk and tree planting operations.

The various input/output alternatives posed by the overall project were evaluated through a linear programming (LP) model using production, harvesting and conversion functions. Side-by-side biomass production evaluations on two dissimilar sites provided a basis for a critical evaluation of the total system. The results of the financial and energy analyses for the first rotation of biomass from commercial plantations managed under alternate strategy/site options indicated the major costs to be irrigation, fertilization and land rent. Nearly 69% of the total cost for the control strategy was attributed to land rent and taxes, management supervision and spray maintenance operations. The remaining 31% was for

the first rotation's prorated cost of plantation establishment. The fertilization strategy added 49% to the base control cost on the Basher site and 66% to the Morrison site. Irrigation tripled the base control cost on both sites.

The energy costs for the control strategy were dominated by land rent. The cost of land, represented as the net energy return from an alternate land use of corn production, was 87% of the total energy costs on either site. Of the remaining energy expended on the first four year rotation, 56% was for spray maintenance operations and 32% was for the first rotation's share of establishment costs. The additional energy expenditure for the fertilization strategy was lower on the Basher than the Morrison site. Irrigation involved an added energy cost on both sites.

The adjusted four year yields of biomass ranged from 33 ODt/ha for the control/Morrison strategy to 43 ODt/ha for the fertilization/irrigation/Basher strategy. The energy output from the control strategy was 50% greater than its total energy cost. Higher net energy returns were realized on the fertilization and/or irrigation strategies.

The financial and energy profiles displayed modest to major limits depending upon the management strategy. The basic problems with the options were using too much relatively expensive energy toward the production of relatively cheap energy and the operational costs. The control strategy followed by the fertilization strategy produced the most favorable economic considerations, even though they had modest negative first rotation returns.

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LIST OF UNIT ABBREVIATIONS

atm	-	atmospheres
°C	-	degree Centigrade
cm	-	centimeter
g	-	gram
ha	-	hectare
h	-	hour
hp	-	horsepower
kcal	-	kilocalorie
kg	-	kilogram
km	-	kilometer
kPa	-	kilo Pascals
ℓ	-	liter
m	-	meter
MJ	-	megajoules
OD	-	oven dry
t	-	tonne
yr	-	year

INTRODUCTION

Forest Biomass Short-Rotation Plantations

Wood as an energy source has received renewed interest, partially based on certain advantageous qualities of short rotation intensively cultured (SRIC) biomass. For example, land requirements needed to supply a multiproduct wood chemical plant for an operational period of 20 years from a traditional forest stand in Pennsylvania are two or more times greater than the land requirements using SRIC biomass from the plantation design in this project (Blankenhorn, P. R. and R. C. Baldwin, in press). A complete determination of the feasibility of using forest biomass as a fuel or chemical source should include silvicultural considerations and net financial and energy analyses of all inputs and outputs from such a production system (Figure 1). Several studies have provided conceptual models of forest biomass plantations and their role in producing wood energy (Howlett and Gamache, 1977; Inman et al., 1977; Rose, 1977; Fege et al., 1979; Rose et al., 1981; Hansen, et al., 1983).

Analysis of the use of SRIC biomass for fuel may be divided into production, harvesting and conversion functions. Decisions concerning the operations in one function influence the other functions. The economic analyses identify, analyze and establish the relative importance and influence a constraint in one function will have on the other two functions, provided the model has an accurate data base. The prioritization of these constraints will identify certain constraints as important in the overall production/harvesting/conversion strategies while other considerations within each of the functions may be suppressed. For example, operational constraints for site preparation in the production function may be considered of higher importance in determining plantation size than planting operations. In addition, site preparation constraints may be determined to be of higher importance than operational costs in the harvesting function or moisture removal costs in the conversion function. However, a reliable feedstock supply for the conversion facility may supercede certain economic considerations (Rose et al., 1981). Ultimately, it will be the market that will influence major decisions in all three functions.

The major thrust of SRIC management strategies is to channel the total growth potential of the land base into optimizing biomass production so the crop can be harvested and marketed. Biomass yields can be optimized by appropriate decisions concerning genetic selection, weed control, cultural treatment, planting density and rotation length. Improved pairing between site and biomass species or variety can double average productivity of short rotation stands (Ranney, et al., 1982).

In the production function, planting density will be influenced by silvicultural, operational and economic constraints. For example, as growing space per tree increases, the number of trees planted per hectare decreases, but cultural investments may increase for longer rotations. As land area per tree increases, the distance between trees within rows and/or the distance between the rows increases, which can change equipment field efficiencies. In addition, planting stock costs per hectare decrease with increasing growing space per tree (Hansen, et al., 1983) and the carrying

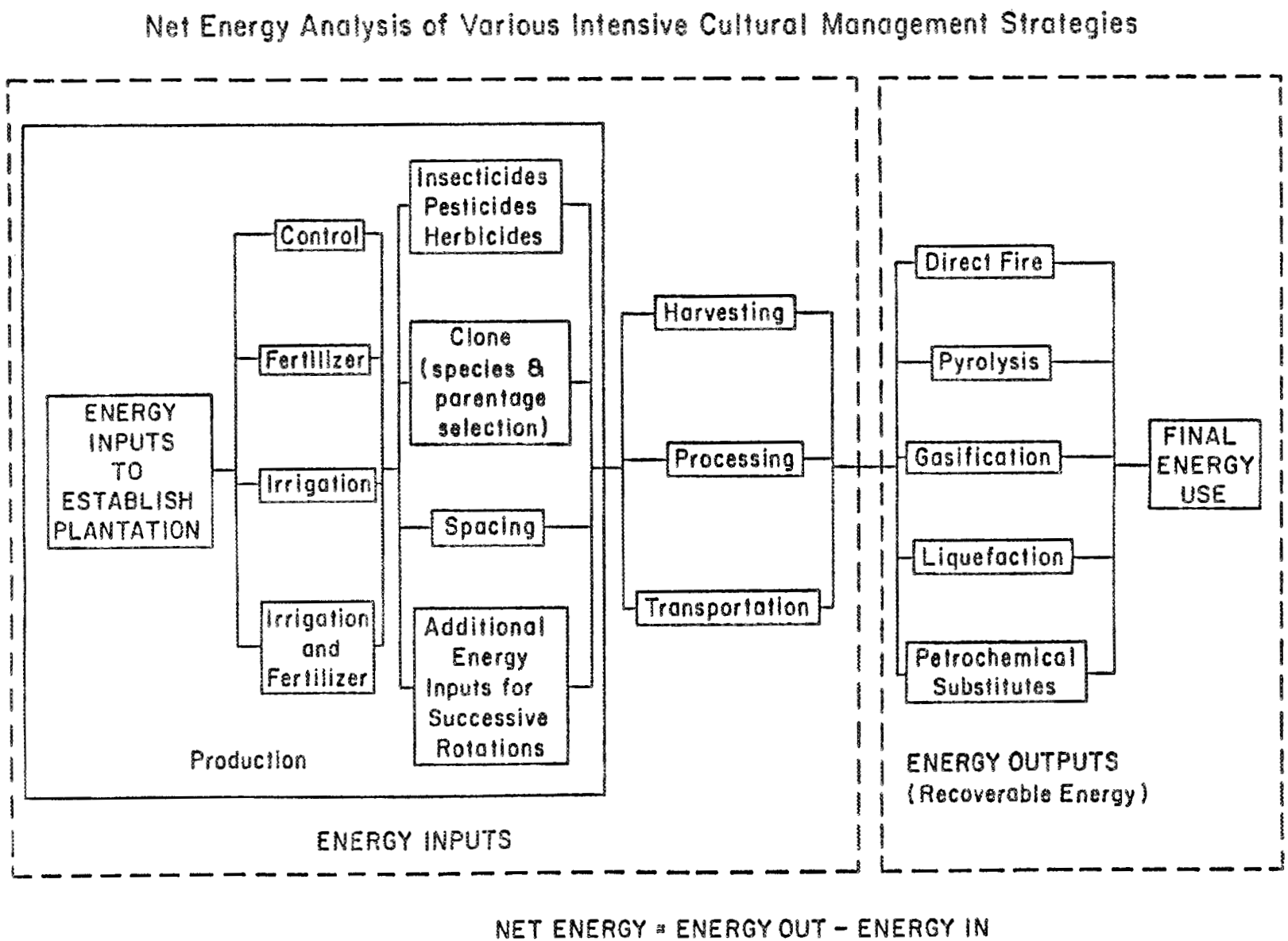

Figure 1. Flow diagram for net energy and financial analyses.

costs increase because of greater rotation lengths. Total land area needed to supply the biomass to the conversion facility must also be considered.

Ribe (1974) summarized a comparison of yields over a wide range of densities and sites and indicated the optimal density to be in the range of one tree per 0.37 m^2 to 1.49 m^2. Ek and Dawson (1976) reported high stand densities (one tree per 0.05, 0.09, and 0.36 m^2) were necessary for high rates of biomass production (17.5, 19.3, and 14.3 ODt/ha/yr) in the first rotation on fertilized and irrigated plantations. These values were projections based on early growth and yield data. Actual yields were considerably lower, with the 0.09 m^2 spaced trees annually producing an average of 5.9 ODt/ha and the 0.36 m^2 spaced trees producing an average of 4.7 ODt/ha for a first rotation of five years (Zavitkovski, 1983). Proper regulation of stand density can shorten the rotation by influencing tree growth and obtaining higher initial yields. More closely spaced trees will have maximum annual production rates at earlier ages than wider spaced trees, but the ultimate maximum annual production rates may be about the same for all spacings. Actual first rotation data for Populus 'Tristis #1' at planting densities of one tree per 0.09 to 5.76 m^2 and rotations of five to 10 years, respectively, indicated an average annual yield advantage for the more dense plantings (Zavitkovski, 1983). Planting density of one tree per 0.09 m^2 averaged 5.1 ODt/ha/yr in a five year rotation and the trees planted at 2.4 x 2.4 m averaged 4.7 ODt/ha/yr after 10 growing seasons. Naughton and Geyer (1982a) have estimated the two to six year old yields for cottonwood growing in eastern Kanses. At six years of age, 7000 trees per hectare (1.4 m^2/tree) were expected to yield 43.3 ODt/ha, and 1400 trees per hectare (7.1 m^2/tree) were expected to yield 29.3 ODt/ha. However, Bowersox et al. (1979) indicated that tree densities and rotation lengths for various Populus spp. may be different on sites of varying productivity potential.

A summary of several studies on short-rotation hardwoods by Fege et al. (1979) indicated annual yields of 9.8 to 19.8 ODt/ha can be realized under intensive management. Cannell and Smith (1980) reviewed the published literature for short rotation forestry in temperate regions and concluded that about 10-12 ODt/ha/yr would be working maximum yields for four to five year old first rotations. Bowersox and Blankenhorn (1979) have projected an annual production of 7.0 ODt/ha for the first rotation, without fertilization or irrigation, for various Populus spp. Bowersox and Ward (1976a) have suggested clone NE-388 (P. maximowiczii x P. trichocarpa) tested on an Edom silt loam soil to be an appropriate clone for close spacings (0.46 m^2) in rotations of less than 5 years. Their research shows standing biomass yields (stemwood, bark and branches) of 7.7 ODt/ha/yr on a four-year-rotation.

Financial returns are realized later and less frequently with long rotation versus short rotation crops (Rose et al., 1981). However, analyses of projected yields reported by Ek et al. (1983) suggest that maximum yields occur sooner in denser plantings (short rotation) and yields from wider spacings (longer rotation) may eventually meet and exceed denser planting yields. These analyses were for a variety of Populus clones with densities of one tree per .09 to 5.76 m^2 and ages of three to 15 years. Optimal planting densities and rotation lengths are likely to be in the one tree per 0.1 to 9.0 m^2 and three to 10 year range, depending on species, cultural investments, location and rotation.

The amount of time it takes for biomass to fully occupy a site at any given spacing depends partly on whether it is undergoing initial or coppice growth. Rose, et al. (1981) report that economic and energy efficiency is not affected by rotation length within the plantations and rotation lengths they evaluated. Initial rotation length decisions may be changed due to the fact that wood can be stored on the stump (Rose, et al., 1981). Rose et al. (1981b) also noted rotation lengths were dependent on insect and disease risks, type of wood product desired and harvest technology.

Continuous yields from Populus spp. plantations can be obtained by the coppicing of these hardwoods. Preliminary indications on existing field trials indicated three to four coppicings appear biologically feasible under intensive culture (Rose, 1977; Malac and Heeren, 1979). It appears that yield from coppice growth exceeds that of first rotation growth (Bowersox and Ward, 1976b; Crist et al., 1983; Ek, et al., 1983). Bowersox and Ward (1976b) evaluated yields on three Populus hybrids using first rotation yields and a second rotation yield equation. Populus hybrid NE-252 (P. cultivar angulata x trichocarpa) and NE-388 were projected to produce the greatest two-rotation OD yields using a first rotation of three years and a second of four years, with tree spacings of 0.46 m^2 (Bowersox and Ward, 1976b). In both cases, second rotation average annual yields were more than double those of the first rotation.

Silvicultural and Management Operations

Site Selection

Site selection for short-rotation biomass plantations involves similar steps to those used in traditional forest management but differs via a more intensive approach (Howlett and Gamache, 1977; Malac and Heeren, 1979). A considerable increase in output and reduction in management costs can be made by choosing the proper site (Fege et al., 1979). Certain conditions should be met to insure the establishment of the plantation cuttings and to maximize their eventual yield. A site should be well-drained, well-aerated and supplied with adequate moisture during the growing season. The level of the groundwater table should be monitored since groundwater within 4 inches of the surface will inhibit plant growth (Malac and Heeren, 1979). Soil composition should be appropriate for hardwoods. Malac and Heeren (1979) recommend soils with sandy loam or loam surfaces fairly high in organic matter and with a thick B horizon of friable sandy-clay to clay loam texture. Bowersox and Ward (1976b) have planted hybrid poplar on an Edom silt loam soil, which is a residual soil derived from calcareous shale and characterized as good in available moisture and native fertility. Site selection must also consider the broader qualities of the land. Attention has focused on topographical features. The land should have minimal slope and few obstructions to accommodate the highly mechanized features of short-rotation systems (DeBell and Harms, 1976). Inman et al. (1977) classified land with slopes greater than 30% as unusable for mechanized plantations.

The logistics of plantation sites, with reference to conversion facilities, have been identified as important cost considerations to the overall supply system. Transportation costs of \$.19-\$.27 per ODt per mile have been estimated (Howlett and Gamache, 1977; Eza et. al, 1984). Blankenhorn et

al. (1978) identified transportation, along with moisture removal, as accounting for about 70% of the total energy inputs for cultural systems. Geyer and Melichar (1982) supported this by concluding that the feasibility of using wood from cottonwood and black locust plantations as fuel was heavily dependent upon transportation and chip-drying costs. However, the competitive advantage of biomass increased when alternative energy products incur greater transportation costs relative to biomass (Spiewak et al., 1982).

Site Preparation

Plantations are likely to be established on marginal, unused and abandoned farm lands since these sites are available for acquisition, generally lower in rental or purchase price than good farm land and more easily prepared than traditional forestland. Rose and DeBell (1978) acknowledge the costs for converting pasture and other agricultural land to biomass systems will usually be less than conversion costs for forestland, particularly if the timber is unmerchantable. Howlett and Gamache (1977) note that shearing, raking, burning and disking are basic requirements in converting forestland to plantation sites, while old-field sites may only require plowing and herbicide applications. Even partially forested sites require intensive slash and stump removal to facilitate subsequent machinery movements. DeBell and Harms (1976) point to revenue earning from wood fiber sales as a means of partially offsetting land preparation costs. Although clearing is costly, it is only a singular expense in the lifetime of the plantation.

Intensive site preparation and weed control, prior to and during the first growing season, are essential to the establishment and rapid growth of cuttings (Blankenhorn et al., 1978). Site preparation, similar to methods used in agricultural row crop production, involves plowing and/or disking in the fall and disk harrowing in the spring prior to planting. These procedures improve aeration and drainage in the soil, increase the acceptance of herbicides and fertilizers, and help control weeds. Malac and Heeren (1979) suggest the ground be subsoiled in the fall if there is a well-developed plow pan or shallow top soil. Beyond the breaking of the plow pan, this allows the soil to mix and settle and eliminates large air pockets in time for spring planting. Thus the cuttings and subsequent root growth are more adequately received and enhanced by the soil.

Hardwood plantations, especially short-rotation, require intensive and regular control of competing vegetation (Malac and Heeren, 1979; Rose et al., 1981b; Naughton and Geyer, 1982). Weeds impede the acceptance and growth of poplar cuttings. Furthermore, the above average fertility of farm lands encourages weed growth. Prescriptions for weed control are site specific with respect to type, amount and timing of herbicide applications and cultivations (Heiligmann, 1975).

In minimal cases, weed control can be obtained relatively easily by disking in the fall (Heiligmann, 1975). However, where this is insufficient, the fall plowing or disking should be accompanied by a total herbicide kill (Heiligmann, 1975). Even with a fall application of a total kill herbicide, the residual or windblown seeds may permit a weed emergence in the spring. Hence, a pre- or post-emergence herbicide procedure may be necessary at planting time. In some instances, weed control management may

be required for the first two growing seasons after planting (Hansen et al. 1979) and at the beginning of subsequent rotations.

Planting

Mechanized planting of closely-spaced hardwood cuttings has had limited success on a commercial level. Many of the experimental stands have been planted by hand. However, machine planting will be an economic necessity in closely-spaced biomass plantations (Howlett and Gamache, 1977). Furthermore, tree spacing will influence the size and type of equipment used in other establishment operations. Also, planting costs increase per unit area at closer spacings (Rose and DeBell, 1978).

The combination of machine planting rates and the length of the total planting season influence plantation size. Based on a case study by Mattson and Miyata (1982) a planting crew of five could plant 180 ha on a 1 x 1 m spacing within 2 months. They indicated a rate of productivity of 0.52 ha/h. For larger areas and smaller spacings, they cite the need for improved planting technology, particularly in the area of automated planting equipment. This would reduce costs and improve productivity. Rose et al. (1981a) estimated machine planting rates of 4818 and 3212 cuttings/ha/h at spacings of 1.21 x 1.21 m and 2.44 x 2.44 m, respectively. Several planters, employed on experimental plots, could meet commercial requirements. According to Cram (1975), two 4-row planters, each utilizing a crew of 10, planted 155,000 cuttings/ha in an 8-hour day with a 1 x 1 m spacing (4843 cuttings/ha/h for each unit). In the work at Rhinelander, Wisconsin, Hansen et al. (1981) reported a planting rate of 5,000 cuttings/h for a 4-row mechanical planter.

Fertilization

Fertilizer is a key component in both conceptual plantation designs (Howlett and Gamache, 1977; Inman et al., 1977; Fege et al. 1979; Rose et al., 1981b) and experimental hybrid poplar plots (Bowersox and Ward, 1976b; Bowersox and Ward, 1977; Zavitkovski, 1979; Hansen et al. 1981). However, the economic evaluation of fertilization on short rotation commercial plantations has been limited.

The prime rationale for fertilizer is increase of growth rates and subsequent yields. Fertilizer may be necessary for the maintenance of optimum growth rates in the early stages of establishment (DeBell and Harms, 1976). Also fertilizers, by reducing nutrient depletion, lower potential insect and disease problems (Fege et al. 1979). Bowersox and Blankenhorn (1979) summarized reported studies on the yields and responses to fertilization of *Populus* spp. In general, *Populus* spp. demands large amounts of nutrients but demonstrates good response to fertilization, particularly from certain elements. Critical nutrient elements include: nitrogen (N), potassium (K), phosphorus (P), calcium (Ca) and magnesium (Mg) (Bowersox and Ward, 1977; Bowersox and Blankenhorn 1979; Bowersox et al., 1979; Fege et al., 1979; Zavitkovski, 1979). Soil evaluations are recommended to determine initial nutrient deficiencies and subsequent residual levels of nutrients. Fege et al. (1979) report that the fertilization strategy should be accompanied by an application of lime at the onset of a rotation. Bowersox and Blankenhorn (1979) further note the

amount and balance of nutrients depend on site, parentage, rotation age and yields.

Fertilizers can be applied with conventional farm equipment before the cuttings are in place. The field efficiencies and capacities of tractors and fertilizer equipment are well documented (Waters and Daum, 1974; Doane Agricultural Service, 1972; ASAE, 1978). Application rates are typical to those in the agricultural sector. After the initial growing season tree heights necessitate fertilization by helicopters. Helicopters also provide a more rapid rate of application, improved access to various sites, and reduce the need for roading within the plantation. Over the past 15 years, more than 9 million acres in Washington and Oregon forests have been fertilized by helicopter with application rates of 168 to 224 kg/ha of elemental nitrogen fertilizer (Miller and Fight, 1979).

Irrigation

Various types of irrigation methods have been reported for agricultural crops and tree fruit crops (Reed *et al.*, 1976; Pimentel, 1980). The supplementing of rainfall, particularly during stand establishment, may be critical to the culture of hardwoods on many sites (Fege *et al.*, 1979). Trickle irrigation is a preferred system due to the reduction of moisture stress on plants and the conservation of both water and energy through the use of smaller wetting areas and low operating pressures (Funt *et al.*, 1980). The potential increased yields from irrigation might justify the added cost if the system is properly matched to the terrain, soil water-holding capacity, size of potential product and water source (Mace and Gregersen, 1975). Irrigated *Populus* 'Tristis #1' and jack pine produced 43% and 13% increases in energy over similar non-irrigated cultures (Zavitkovski, 1979). The travelling gun system used by Hansen (1983) increased biomass yield by 76% in year two and by 44% in year three over non-irrigated trees.

Properties of Populus Biomass

Utilization of short-rotation forest biomass as a source of energy and chemicals will depend on physical and chemical properties such as: 1) gross heat of combustion, 2) extractive content, 3) specific gravity, 4) holocellulose content, 5) lignin content, 6) alpha-cellulose content, 7) ash content and 8) moisture content. There appear to be differences in chemical and physical properties associated with tissue component, tissue age and parentages (Bendtsen, 1978; Murphey *et al.*, 1979; Bowersox *et al.*, 1979; Cheng and Bendtsen, 1979; Geyer, 1981; Bendtsen *et al.*, 1981; Blankenhorn, *et al.*, 1985). Measurement and comparison of the fuel and chemical properties within a clone and among clones will aid in clonal selection and establish basic data needed to efficiently utilize short rotation forest biomass.

Types of Economic Analyses

The basic design in the micro-analysis of a production system considers the ability of the system to generate a sufficient financial gain from its output to meet the combination of fixed and variable costs. In most instances, the system is considered from a short run viewpoint where the

size of the capital investment and its technological state are fixed. With the advent of energy plantations, variations in this analytical design could include being critiqued on both a financial and energy unit equivalent basis. Regardless of the common denominator used throughout the system, the costing structure is usually stratified in terms of the fixed costs of the capital inputs and the variable costs tied to labor, raw materials and related inputs.

Christiansen (1979) lists five approaches for evaluating the cost of the capital investment: 1) discounted present net worth (PNW), 2) compounded future net worth, 3) equal annual equivalent, 4) internal rate of return and 5) benefit-cost ratios. The cost of using capital may be explicit, such as the interest rate charged to a loan, or implicitly referenced to as the opportunity cost foregone from not using the funds in an alternate pursuit (Christiansen, 1979). Interest charges can be calculated as "net of inflation," noted as real rates of return. Klemperer (1979) reported a 6% historic and projected after-tax real rate of return on U.S. corporate capital. Row et al. (1981) proposed a real rate of 4% to reflect the current long-term market expectations of returns of new productive investments.

An established procedure for analyzing the financial merit of investment propositions involves discounting future costs and revenues to a common present day value. Flick et al. (1979) demonstrated the profitability of loblolly pine plantations using discount analysis. Present net worth (PNW) measures the current net value of all future discounted revenues and future discounted costs. Flick et al. (1979) indicated the PNW's of forestry investments were most sensitive to interest rates, price changes, yields influenced by site quality and stand-establishment costs. Benefit-cost (B-C) ratios were an alternate discounting approach to investment analysis. The B-C ratio of an investment project was the ratio of the discounted future revenues over the discounted future costs (Christiansen, 1979).

Several studies have been made on the financial performance of forest biomass short-rotation plantations. Rose (1976) developed an economic model using cost and yield information to calculate financial measures of PNW, internal rate of return and payback period. A simulation program was also used to determine the effects of various factors influencing costs. Rose (1977) utilized his economic model to further determine likely ranges of biomass production costs for a number of production alternatives and intensities. Eight management alternatives for intensive culture were designed to analyze the cost of producing energy from wood and the cost of fiber for pulp processing (Rose, 1977). Rose and DeBell (1978) evaluated break-even requirements of various intensive-management cultures by employing a sensitivity analysis of input and output variations to the production function. Inman et al. (1977) used a financial model of a silvicultural farm to determine: 1) the net return generated through alternate biomass prices, 2) price requirements for meeting particular rates of return on equity and 3) discounted cash flows.

Bowersox and Ward (1976b) performed an economic analysis on a short-rotation fiber production system for hybrid poplar. The objective was to calculate the costs of producing and harvesting stemwood, bark and branches from three Populus hybrids managed under various length first-second

rotations and spacing strategies. All costs were compounded forward at a 6% rate in determining the future compound costs per unit of output at the end of a second rotation. A similar analysis looked at the effects of fertilization strategies.

Rose et al. (1981b) undertook a financial analysis of hybrid poplar plantations in the Lake States. Costs and revenues of various production systems were evaluated over a 30-year planning horizon. The present net worth and internal rate of return were used in evaluating various factors of production and their related yields (Rose et al., 1981b).

Several studies have employed energy concepts as common denominators in their economic analysis of intensive biomass cultures. Blankenhorn et al. (1978) established a net energy analysis scenario whereby energy inputs were contrasted to recoverable energy from two distinct cultural systems. The analysis evaluated various sites under consideration and identified the major energy-consuming operations when forest biomass was used as a fuel source (Blankenhorn et al., 1978). Zavitkovski (1979) analyzed energy budgets for irrigated, intensively cultured plantations of Populus 'Tristis #1' and jack pine in northern Wisconsin. He examined the total energy available and used ratios of energy output to energy input. The preferred strategy for analyzing energy relations in forest plantations is net energy returns (Blankenhorn et al., 1978; Zavitkovski, 1979). The energy output/input ratios indicate the marginal efficiency of using energy inputs in the production of biomass and energy. They were viewed as complementary and supportive indicators. Zavitkovski (1979) calculated ratios for three stages of forestry operations: a) on the stump, b) for harvested and chipped material and c) for dry chips. Geyer and Melichar (1982) also obtained output/input energy ratios for five-year-old cottonwood and black locust plantations in Kansas.

Financial Input-Output Measures

Limited information is available on commercial biomass production systems. Cost estimates have been established for commercial biomass systems based upon similarities in the proposed systems with the commercial agricultural and forestry sector. The proposed management systems are similar to agricultural production and in most cases similar machinery has been proposed (Blankenhorn et al., 1978). Cost estimates for site preparation and establishment of short-rotation plantations have been developed (Mace and Gregersen, 1975; DeBell and Harms, 1976; Inman et al., 1977; Rose et al., 1981b).

Rose reported the financial feasibility of intensive cultures was most sensitive to site preparation costs and needs, planting costs and spacings (Rose, 1976; Rose and DeBell, 1978). The study by Rose and DeBell (1978) pointed to the importance of spacings. Trees coppiced at 4 and 10 year cycles, and at wide spacings (1.22 x 1.22 m, 3.05 x 3.05 m) appeared feasible, while 2-year coppice rotations, at higher densities (0.61 x 1.22 m), did not. Mattson and Miyata (1982) estimated planting costs of $97.87/ha at 1 x 1 m spacings and predicted lower costs at wider spacings. DeBell and Harms (1976) also indicated the cost of planting may be the largest single expense in the production period. Certain operations within the production function might be less expensive if subcontracted to outside firms instead of owning and operating equipment or machinery.

Fertilization costs for biomass systems were analyzed by Inman et al. (1977). They concluded this expense was a function of regional cost variations of materials, the varying costs of the types of application methods and the type of species planted (Inman et al., 1977). Fertilizers have undergone significant price increases during the past decade and required continued assessment as to their impacts on profitability (Rose and DeBell, 1978). However, Bowersox and Ward (1976b) found that the increased yields of certain hybrid poplar clones, as gained through fertilization, decreased the unit cost of fiber.

Irrigation costs were shown by Reed et al. (1976) to vary according to the irrigation interval, volume of water applied and the type of system employed. In turn, Mace and Gregersen (1975) stated that the irrigation intervals are regulated by soil-water holding capacity, evapotranspiration, volumes of water applied per irrigation and desired soil-water content. Investments in irrigation systems were known to be extensive (Rose et al., 1981b). Installation costs ranged from $500 to $2000/ha, with annual operation and maintenance ranging from $100 to $250/ha (DeBell and Harms, 1976; Reed et al., 1976). However, Mace and Gregerson (1975) pointed to a void of data on the physical, biological and financial parameters of potential irrigation systems. Rose et al. (1981b) provided cost estimates for a travelling gun system. They found irrigation to be financially unattractive due to the large cost of fuel usage. Rose et al. (1981b) suggested costs could be reduced by adopting different technology or by irrigating only during the first few years of each rotation. In a comparison study, Funt et al. (1980) found the installation costs of a trickle system to be 50% of a travelling gun system. Trickle systems were more expensive than travelling gun systems to operate and maintain for low-density crops such as apples but much less costly for higher density crops such as grapes.

The cost of land as an input in the production function can be referenced as rental fees, purchase price or the opportunity cost of alternate uses (Bowersox and Ward, 1976b; Rose et al., 1981a; Naughton and Geyer, 1982). DeBell and Harms (1976) indicated fluctuating prices for agricultural crops have a logical impact on the rental or lease rate of even marginal and submarginal lands. Net returns for various agricultural crops in Pennsylvania have been documented (Pennsylvania Department of Agriculture, 1982; Dum, 1982). Naughton and Geyer (1982) capitalized the net returns from agricultural pursuits to determine land values and associated annual charges for using this resource. Bowersox and Ward (1976b) valued land at 6% of its average fair market value. Rose et al. (1981a) assessed land costs via an average price paid for cleared agricultural land in the Lake States. This was based on estimates of land availability and probable tract sizes.

The market values of biomass output have been assessed in several ways, most commonly as wood chips. Rose et al. (1981a) used $12.50/green ton delivered, or $25/OD ton as representative prices in the Lake States. These were based on the prices paid by industrial users of wood fiber, particularly pulp mills. In a study by the Department of Energy, costs were projected to be $20 to $34/OD ton for hardwoods grown under 6- to 10-year rotations (Fege et al., 1979). The Minnesota Department of Natural Resources (1984) reported biomass market values at $43 to $68/OD ton for

pulp and $30 to $68/OD ton for energy. Financial comparisons have been made with alternate energy sources in valuing biomass (Spiewak et al., 1982). On-site prices for coal, natural gas, oil and various field crops have been documented (Energy Information Administration, 1982; Spiewak et al. 1982). Rose et al. (1981b) indicated the most important factors affecting the investment performance of biomass systems are yield and the market price.

Energy Input-Output Measures

The estimated energy costs for machinery, materials and related equipment are required in developing energy expenditures for plantation operations. Accounting conventions for the energy analysis of farm machinery (Pimentel, 1980) and the engineering and operational particulars on various types of farm equipment, to complete these energy analyses, are readily available (Doane Agric. Service, 1972; Waters and Daum, 1974; McCurdy, 1975; Implement and Tractor, 1981).

Geyer and Melichar (1982) reported most of the energy used in silvicultural operations was in fuel, with plowing and planting being the most expensive functions. Zavitkovski (1979) also supported this by noting fuel consumptions in silvicultural operations of 73.2 x 10^3 and 53.5 x 10^3 MJ/ha on 10-year rotations of Populus and jack pine, respectively.

Naughton and Geyer (1982) found areal energy yields and areal energy costs both increasing as plant density increased. However, maximum plantation yields were obtained sooner with increased plant density. Their "least cost system" involved reduced plant densities (1400 trees/ha), intensive weed control, and coppice harvest cycles. Blankenhorn et al. (1978) showed labor energy to be insignificant in the energy budgets for their silvicultural systems.

A measurement system for determining the energy used in the manufacture and transport of fertilizers and herbicides was also developed by Pimentel (1980). Fertilizers were substantial energy consumers (Blankenhorn et al., 1978; Zavitkovski, 1979). Zavitkovski (1979) found fertilization accounted for 45% of the total establishment energy for P. 'Tristis #1' plantations, with the manufacture, transport and application of nitrogen accounting for 81% of the total. Blankenhorn et al. (1978) noted that 16% of the energy consumed in all operations of an intensive culture, on a 10-year rotation, could be attributed to fertilizer.

Irrigation can be an energy intensive input (Zavitkovski, 1979; Rose et al., 1981b). The initial investment of energy and subsequent annual energy costs were given in Pimentel (1980). Total irrigation energy for Populus and jack pine systems was approximated by Zavitkovski (1979) at 5507 MJ/ha/yr. However, Zavitkovski noted that energy invested in producing biomass might bring proportional returns.

Energy comparisons have been made among various types of irrigation systems. Pimentel (1980) compared the nine most commonly used irrigation system types. The solid set sprinkle and the trickle had the highest annual fixed energy inputs, 6018 and 4215 MJ/ha/yr, respectively. However, the surface runoff return and the trickle had the lowest pumping energies

required when applying water at various lifts (Pimentel, 1980). Funt et al. (1980) noted that trickle irrigation, compared to the travelling gun sprinkler system, used 54% less water and 74% less energy per year in supplying the same plant requirements.

Energy plantation outputs have been measured and incorporated into economic analyses. Zavitkovski (1979) researched the biomass (ODt/ha) and energy content for P. 'Tristis #1'. Tree components included stem wood, stem bark, branches, foliage and roots. Yields were evaluated on a dry-weight basis, with stem wood accounting for 58% of the total and foliage less than 4%. Blankenhorn et al. (1978) also underscored the following physical parameters as important measures of forest biomass: particle size, moisture content, gross heat of combustion, usable heat, proximate analysis, ultimate analysis and chemical content.

Economic Evaluations

Past research has revealed the financial and energy requirements of short-rotation, biomass plantations and the market sectors which might benefit from these plantations. Dutrow and Saucier (1976), working with short-rotation systems of coppicing sycamore, concluded that only industrial landowners would find production profitable. They also felt the capital limitations of non-industrial landowners would prevent this ownership group from investing in such ventures. Rose (1977) supported this by stating that under existing technologies and costs, wood as an energy source would only be competitive in certain production situations. The use of biomass for pulp and paper processing appeared to be the better alternative at current market prices for certain species. However, as conventional fuel prices rise, continued reevaluations should be made of biomass as an energy source (Rose, 1977; Spiewak et al., 1982). Current studies indicated biomass was not competitive with conventional energy sources in such markets as the commercial sector, manufacturing, transportation or electric utilities (Spiewak et al., 1982).

A Department of Energy study indicated a future potential for silviculture biomass farms in the energy market at competitive prices (Fege et al. 1979). Forest biomass was a major energy source in the forest products industry, in farm applications and in home heating (Spiewak et al. 1982). Geyer and Melichar (1982) indicated fuel costs for petroleum and natural gas were 125 to 200% higher than for woody biomass. Biomass was also evaluated by Spiewak et al. (1982) as being competitive with coal in New England, the Middle Atlantic States and the Gulf Coast, particularly where coal transportation costs are high.

Short-rotation systems may also prove attractive to private landowners willing to commit existing manpower, equipment, and land to such ventures at below market price (Bowersox and Ward, 1976b). Plantations may be justified for providing a secure source of raw material close to the mill site (Bowersox and Ward, 1976b; Rose et al., 1981b).

Linear Programming

Linear programming (LP) is a quantitative method having the capacity to characterize alternative approaches and constraints to biomass production.

The LP technique identifies an optimal solution while operating under a given set of constraints. In this manner the solution represents the most efficient strategies for meeting the operational objective of the system.

Kent (1980) credits LP as bridging the gap between the determination of alternate forest plans and the selection and ultimate implementation of some optimal plan. Three main functions, particularly suited for analysis of a forest plantation system, can be realized through LP. First, there is an organized storage of data as vast amounts of information can be brought together and synthesized. Data is provided through scientific and management planning actions. Secondly, the LP technique involves an allocation of resources as part of the optimal solution. LP insures the solution is consistent with the capabilities of the land base through the incorporation of managerial and environmental constraints in the model. Last, sensitivity analysis of alternate strategies can be employed through reformulations of the initial problem. Hence, alternate plans can be generated (Kent, 1980).

The structural and operational nature of LP makes it particularly useful in the study of economic problems. One of the earliest applications of LP included the analyses of interindustry economics based on Leontief's input-output models (Ignizio, 1982). Government, business and agricultural concerns utilize LP as a decision-making aid for a wide variety of problems. Allied applications that tie to the analysis of a biomass plantation system include: resource allocation, production planning, investment planning, energy modeling and planning, crop production and forest management policies.

Early applications of LP in forestry dealt with timber harvest scheduling, wood procurement, mill management, product distributions, inventory control and land-use planning (Bell, 1977). Current applications include forest-planning, programming and budgeting (Bell, 1977). Forest resource allocation problems, such as timber management and harvesting, were approached through expanded use of the technique. Ware and Clutter (1971) employed LP to develop a programming system for the management of industrial forests. This model maximized financial returns within volume and acreage constraints. Bare (1978) used an LP model to maximize the discounted cash flows of simulated forests under particular rotation strategies. Volume and areal constraints were utilized in accordance with stand management plans. Field (1977) cited expanded use of LP in both the private and public sectors of forestry. Newnham (1975) developed a computer model which converted stand harvest data into an LP matrix in order to evaluate one-year logging plans in eastern Canada. A least-cost logging plan was generated under particular resource limits and management policies (Field, 1977). The most extensive use of LP in the public sector occurred within the U.S. Forest Service in their Resource Planning Act analysis of national forests with the LP models, FORPLAN 1 and FORPLAN 2. These efforts were directed to maximizing the present net worth of various forest outputs and services under the mandates of multiple use management and various resource constraints.

Goals and Objectives

This project was divided into two general, but related, areas. The purpose of the first overall area was to determine growth characteristics and biomass yields for a Populus hybrid grown under four management strategies on two dissimilar sites. The purpose of the second overall area was to expand the biomass production data into complete net financial and energy analyses. In order to complete these objectives, biomass production data were combined with certain laboratory data and economic modeling techniques. Critical biomass production data were coupled with selected fuel, chemical and nutrient content data to establish an array of production inputs for an LP model depicting alternative production/utilization strategies. This project was unique because it incorporated the culturing and managerial aspects of biomass production with the utilization characteristics of the material and evaluated the complete system through a financial and energy framework.

The financial and energy analyses in this project were based on a self-owned, fully integrated commercial-scale operation. Costs for nursery stock, establishment and cutural maintenance operations were developed from field data obtained in this project, and combined with operational information in the literature supplemented by consultations with agricultural engineers and professional farm managers. These production costs were coupled with harvest, transportation, storage and conversion costs obtained from the literature for use in analyzing the commercial-scale operation from production through conversion.

The financial and energy analyses for this project contrasted the inputs for producing, harvesting, transporting and processing biomass against the potentially recoverable outputs from the forest biomass. Comparisons of the financial and energy analyses established the relative importance of the constraints within each function and the sensitivity of various inputs within the overall energy recovery systems. Linear programming analyzed the complete system and compared selected management and conversion strategies, particularly where ranges in the input values were available.

Specific Objectives

The following specific objectives for the project were designed to generate the critical data necessary to complete the project. These were collected within three tasks with specific objectives.

Task 1 - Plantation Establishment - Task 1 analyzed the establishment function for short-rotation plantations under four management strategies (control, irrigation, fertilization and fertilization/irrigation) on two dissimilar sites and determined the financial and energy inputs for these establishment functions. Objectives were to:

1. Establish short-rotation plantations on two dissimilar sites under four management strategies. Using plantation establishment operations, estimate baseline financial and energy data needed for commercial operations.

2. Determine appropriate levels of fertilizers and establish baseline financial and energy data appropriate for this operation.

3. Establish, operate and maintain an irrigation system for short-rotation plantations and determine baseline financial and energy data appropriate to this commercial practice.

Task 2 - Plantation Biomass Production - Task 2 measured biomass production yields, growth rates and properties of the biomass as a fuel or chemical feedstock and to determine the financial and energy inputs needed to operate and maintain the plantations under the selected management strategies.

4. Establish biomass yields and growth values as a function of site quality in the selected management strategies for the first rotation.

5. Establish a range in expected biomass yields and growth values as a function of site quality for the selected management strategies for the first rotation.

6. Establish financial and energy costs for producing biomass on two dissimilar sites under four management strategies (control, irrigation, fertilization and fertilization/irrigation) for the first rotation.

7. Measure biomass properties related to their use as fuel or chemicals and determine the variations in these properties as affected by the selected management strategies.

Task 3 - Analysis of Biomass Financial and Energy Data - Task 3 analyzed the financial and energy data among the selected management, harvest and conversion scenarios. Linear programming was used to analyze the various input requirements, associated constraints and outputs among the combinations of various management, harvest and conversion scenarios.

Objectives were to:

8. Compare the financial and energy data from this project with similar analyses in the literature.

9. Establish net financial and energy analyses for selected conversion strategies for each of the management strategies investigated during this research.

10. Analyze the sensitivity of the financial and energy outputs from each conversion strategy with respect to various financial and energy inputs.

11. Compare the financial and energy analyses for the selected management and conversion strategies to determine the relative advantage of each plantation site.

12. Recommend a management strategy for each conversion strategy with the most favorable financial and energy considerations.

PROCEDURES

Task 1 - Plantation Establishment

Populus hybrid short-rotation intensive culture (SRIC) plantations were established under four management strategies (control, fertilization, irrigation and fertilization/irrigation) on two sites representing favorable (Basher silt loam soil) and unfavorable (Morrison sandy loam soil) inherent growth conditions. Each plantation site (1.2 ha) consisted of six replications (0.2 ha each) with three replications planted in 1980 and three replications planted in 1981. Each replication included four treatment units (0.05 ha each for control, fertilization, irrigation and fertilization/irrigation). Growing space for *Populus* hybrid NE-388 cuttings was 0.48 m^2 with 0.8 meters between rows and 0.6 meters between trees in the rows. In each treatment unit, trees were designated for both continuous inventory and annual destructive sampling over a four year period (Figure 2).

A fertilization schedule based on attaining a corn silage yield of 47 ODt/ha was applied each year to the appropriate treatment units of the 1980 and 1981 plantations. The intent of the fertilization treatment was to amend each site with a balanced N-P-K-Ca-Mg nutrient set so as to achieve equal enhancement of available macronutrients on both sites. This was insured through soil testing and soil specific recommendations. The soil fertility status of each site was evaluated annually and fertilization treatment units were amended to maintain a non-limiting nutrient status. These data were continually compared to soil nutrient changes in the non-fertilized treatment units.

A trickle irrigation system was installed in 1981 to determine growth relationships of the biomass with enhanced soil moisture. Water available for growth is the amount between field capacity and permanent wilting point. The irrigation system was designed to maintain soil moisture above the 50% available water level on the irrigation replications at both sites. Since the water-holding properties of the soil were different at each site, moisture relationships in the rooting zone were determined early in 1981.

Soil moisture levels in the upper rooting zone were monitored at 5 cm intervals by Troxler Model 3401 surface moisture density gauge, and in the lower rooting zone at 30 cm intervals by a Troxler Model 1257 depth moisture gauge. The measured soil moisture values in the upper 20 cm of the soil were used to determine the frequency and volume of irrigation applications. In the event of monitor equipment failure, rainfall and standard agronomic water stress indicators were used to determine irrigation needs. Moisture levels were maintained on the irrigation replications each year above the midpoint between the wilting coefficient and field capacity through uniform irrigation.

Task 2 - Plantation Biomass Production

Biomass yields, growth values and properties were measured and evaluated as a function of management strategy, age and site. A flow diagram for the data collection is given in Figure 3. The timetable for plantation maintenance and data collection is shown in Figure 4. Short rotation

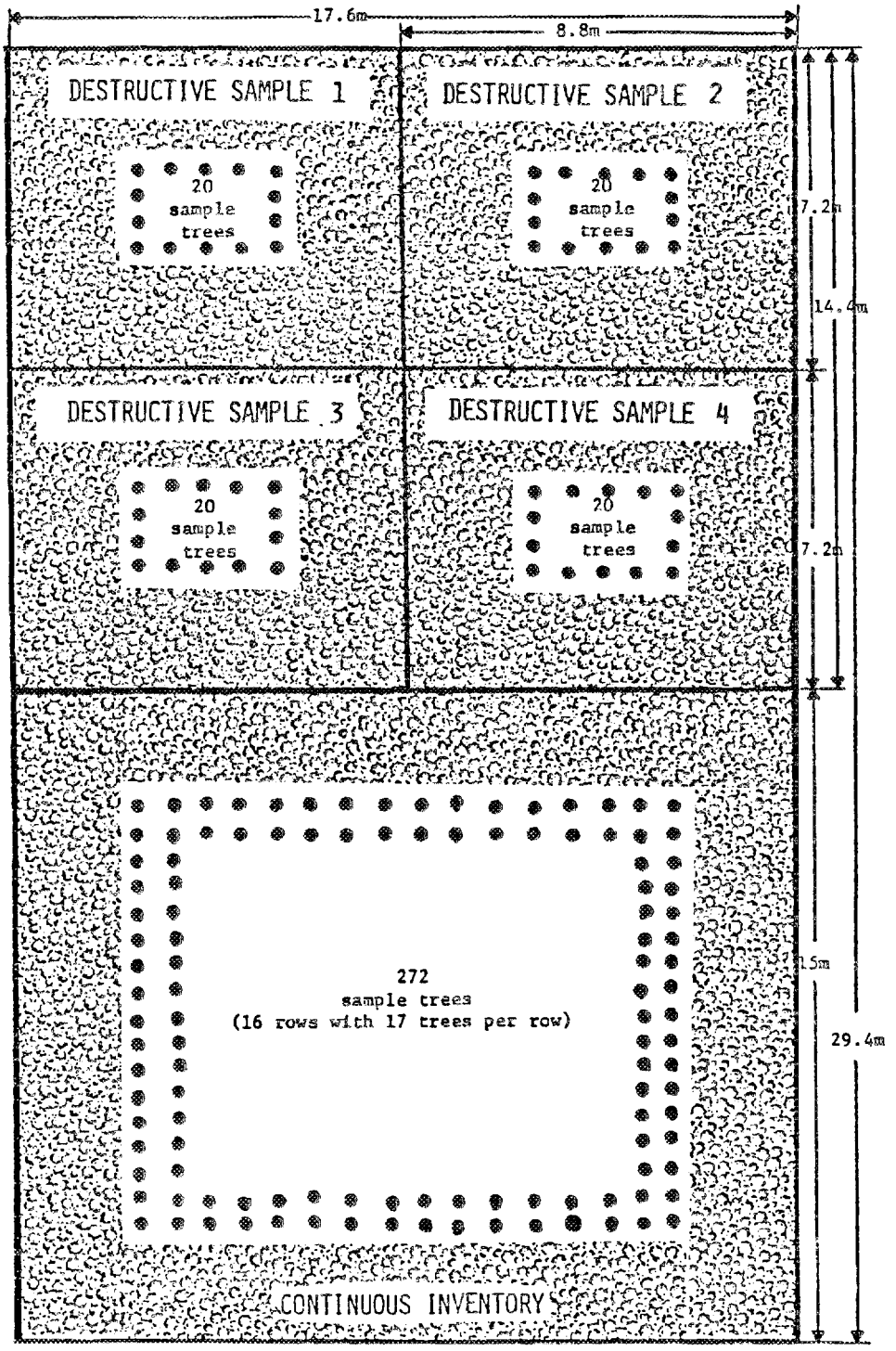

Figure 2. A diagram of the destructive and continuous inventory sample plots for one treatment unit.

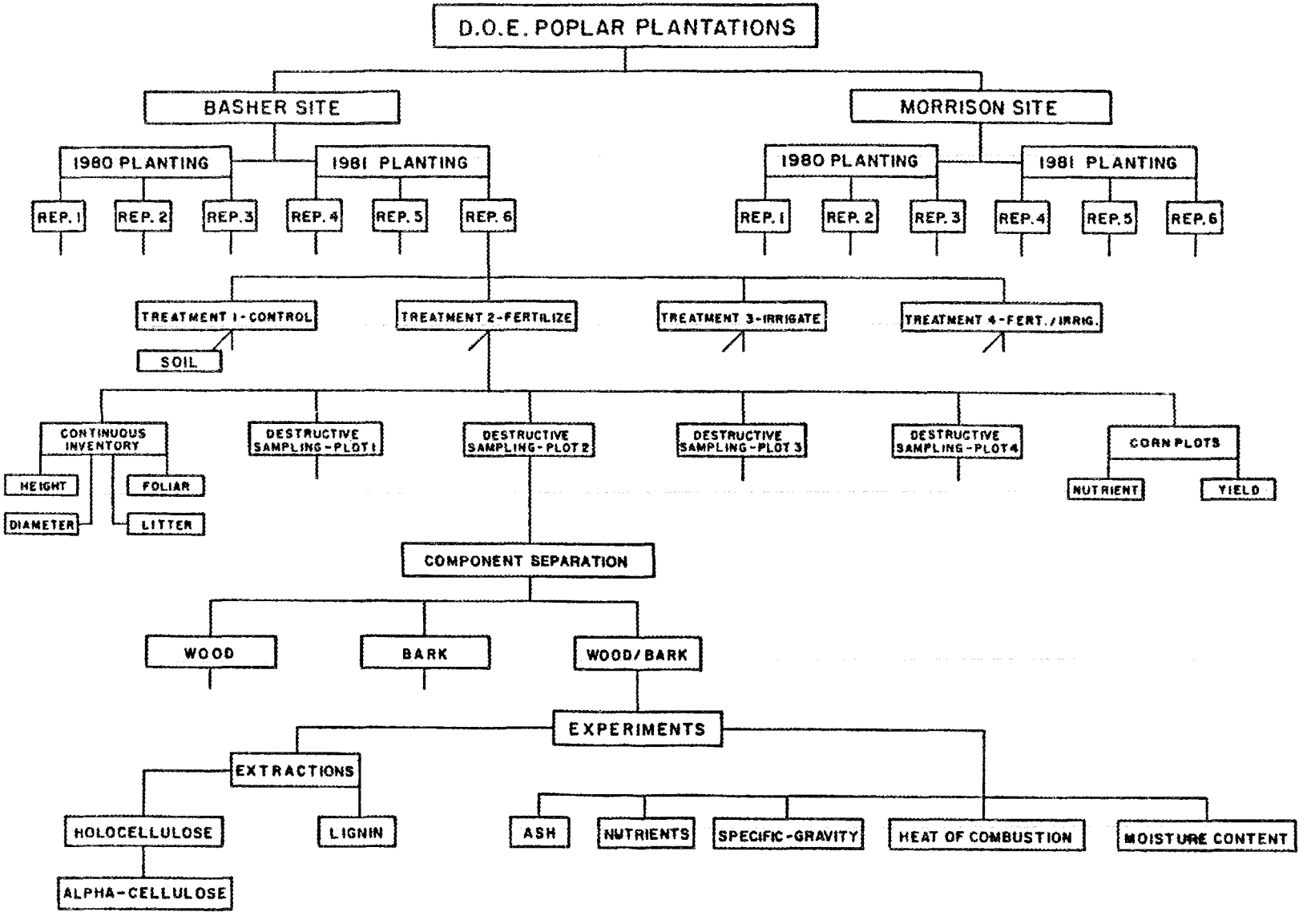

Figure 3. Generalized flow diagram for data collection.

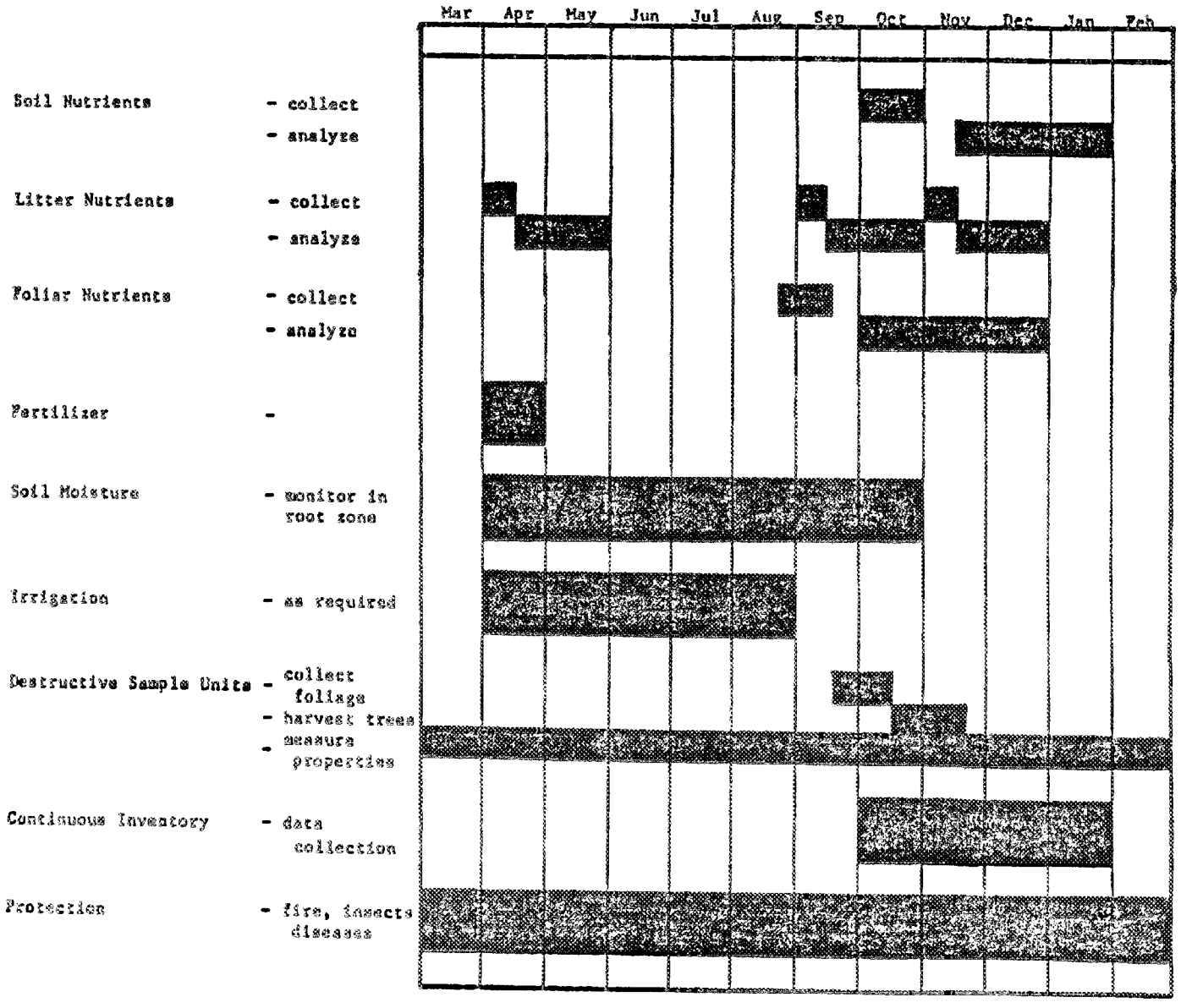

Figure 4. Schedule of annual maintenance of and data collection from project plantations.

intensive culture (SRIC) financial and energy inputs needed to operate and maintain the plantations under the selected management strategies were determined.

Foliar, litter and soil samples were collected annually and analyzed (by the tissue and soil testing laboratories at The Pennsylvania State University). Mature leaves from the upper crown were collected annually from representative trees later in the growing season before leaf discoloration. Annual litter samples were collected at three times during the year: 1) November, 2) April and 3) September. Foliar and litter samples were analyzed for N, P, K, Ca and Mg. Annual soil samples from the rooting zone were collected after each growing season. All soil samples were analyzed for P, K, Ca and Mg. The soil analyses also measured pH, cation exchange capacity and base saturation.

Fertilizer was applied annually to appropriate treatment units in the plantation depending on soil testing results and recommendations. Soil moisture was monitored throughout the growing season, with the trickle irrigation system maintaining soil moisture at near optimum levels for tree growth on appropriate treatment units. These data were compiled, comparatively analyzed and included in the LP financial and energy analyses.

Oven dry yield equations and properties of the biomass were developed from the destructive sample plot data. Green stem diameter (15 cm above ground) and total height data were used to develop oven dry mainstem wood, mainstem bark, branch and total tree weight equations for each treatment and age. These results were applied to the tree size values collected from the continuous inventory plots to determine quality and quantity of the biomass produced by management strategy on each site.

Specific destructive sample plots for each age, treatment and site were evaluated. Foliage on specific destructive sample plots was collected at the end of each growing season. These samples determined foliar tissue production values that, when used in conjunction with foliar nutrient concentration levels, established the amount of nutrients assimilated in the leaves and also the foliage to wood-and-bark production ratios.

The continuous inventory plots were annually measured for tree survival, stem diameter at 15 cm above ground and total tree height. These data, when combined with the oven dry weight equations, determined biomass yields per unit area by age, site and treatment during the first four growing seasons. Actual field weights for all four year old living continuous inventory trees were determined at the end of the first rotation. These data were summarized by individual plots and were used to adjust first rotation oven dry yield estimates. The oven dry wood, bark and total tree yield values were used in conjunction with the moisture, physical and chemical contents to establish SRIC cultural, financial and energy values for usable products in the LP model in Task 3.

Individual sample trees (maximum of 20 trees per treatment, and replicated six times per site) were harvested in November-December and returned to the laboratory for further analyses. Wood, bark and wood/bark specimens by site, age and management strategy were separated from the trees. The one

year old specimens were collected from growth produced in the first growing season of the rotation. The two year old specimens were a combination of one and two year old tissues, the three year old specimens were a combination of one to three year old tissues and the four year old specimens were a combination of one to four year old tissues.

Fuel and chemical values for the trees by site, management strategy, age and component were obtained using the following test procedures: 1) specific gravity (maximum moisture content method, Smith, 1955), 2) moisture content (ASTM D-2016), 3) gross heat of combustion (ASTM D-2015), 4) ash content (ASTM D-1102), 5) nutrient content (N, P, K, Ca and Mg), 6) extractive content (ASTM D-1105), 7) holocellulose content (acid chlorite method, Browning, 1967) 8) alpha cellulose content (ASTM D-1103) and 9) Klason lignin content (ASTM D-1106) of wood, bark and composite wood/bark specimens.

Chemical analysis of bark may be difficult because of the suberin and other wax-like substances in the bark. In a preliminary study, chemical content data was obtained for untreated bark and bark pretreated with a mild alkali solution used to remove the suberin. The results of this study indicated that the suberin did not hinder the chemical determinations except for alpha cellulose. Hence, pretreatment of the bark with a mild alkali solution was not used for the bark and wood/bark chemical content determinations.

Filtration through ground bark specimens was difficult during alpha cellulose determinations. Numerous tests on 2.0 g and 0.5 g bark specimens yielded comparable results. Therefore, alpha cellulose determinations of bark were performed on the smaller specimen size because of ease of filtration.

Statistical analyses included analysis of variance for treatment effects and regression analysis to establish predictive equations. All effects were established at a 0.05 level of significance.

The plantations were constantly monitored for fire, insect, disease and animal problems. Applications of insecticides, fungicides and herbicides, if needed, were in accordance with environmental standards.

Task 3 - Analysis of Biomass Financial and Energy Data

This task analyzed and compared the financial and energy data for the selected management, harvest and conversion scenarios. Biomass yields, growth values and properties from this project were combined and used in the development of a commercial model of a biomass production system. Linear programming was selected to analyze the various combinations of production, harvest and conversion alternatives. The overall LP design structured the production function into separate units following the sequential order of the project: 1) biomass production, 2) harvesting and transportation, 3) storage and 4) conversion of biomass to energy. Each unit was further stratified to represent alternative methods of accomplishing the unit's central purpose.

The structure and interpretations of the problem were in keeping with a general LP format:

1) MAX (or MIN) $Z = \sum_{i=1}^{n} C_i X_i$ as the objective function

C_i = coefficient measures; objective value per unit of activity variable
X_i = activity variable

2) Subject to system of constraints,

$$\sum_{i=1}^{n} \sum_{j=1}^{m} A_{ij} X_{ij} \leq B_j$$

A_{ij} = coefficient measures; resource value per unit of activity
X_{ij} = activity variable
B_j = resource availability

3) and a non-negativity requirement for the activity variable.

$$X_i = \geq 0$$

Objective Function

Two alternate objective functions were used in the LP design: 1) maximization of the net financial values generated by the production system while meeting an allied set of operational constraints and 2) maximization of the net energy from the biomass system while meeting various operational constraints imposed on the system. The financial objective function identified the present net worth of the particular management strategy coming into solution. All costs and revenues in the model were subject to investment analytical techniques using an alternate rate of return of 5%. Although only one of the objective functions was used within any run of the model, the alternate objective was employed as a constraint, with the model either accepting the "open ended" generation of financial or energy values from the constraint or having to meet some lower limit constraint value.

Activity Variable

The activity variable, x_i, served as the common denominator with the LP design. In this model it represented one hectare of land brought into solution from any given management strategy. The diversity of strategies required a system of identification. The activity variable was differentiated on the basis of the following: 1) year of employment, "i", 2) soil type, "j", 3) management strategy, "k", and 4) silvicultural or managerial treatment, "l", under the kth strategy. This permitted all combinations of silvicultural treatments, associated with specific management strategies, as applied on different soil types, to be evaluated in terms of their net financial and energy performances over a certain production time period. The activity variable, X_{ijkl}, represented this general form. Also, any sequence of individual treatments within a

particular strategy was linked together. This linkage functioned as a constraint, subjecting each hectare of land brought into solution, within a particular strategy, to the required sequence of treatments. In this manner, the combination of treatments found in a particular strategy was tested against all other strategies in terms of the objective function.

Coefficients for the LP Model

The objective function coefficients defined the value per activity unit associated with the establishment, maintenance, and yields of the biomass system. The C_{ijkl} values represented financial (or energy) inputs or outputs per hectare of land. Their product with the activity variable (C_{ijkl} X_{ijkl}) determined the total financial (or energy) commitment associated with the volume of land brought into solution (e.g., energy/ha x ha = total energy).

The A_{ijkl} coefficients, found within the system of constraints, further described the LP model structure. The A_{ijkl} represented the operational value per hectare of land used to describe operating conditions under which the various strategies were influenced or bound. Their product with the activity variable (A_{ijkl} X_{ijkl}) determined the operational commitment associated with the volume of land brought into solution under the constraint equation.

Constraints

As previously indicated, the solution of an LP problem was achieved under the tandem forces of the objective function and a set of constraints. The optimal solution to the problem was established via the influence of these constraints. The constraint equations used in this model described: 1) financial or energy limits, 2) land area and 3) the required sequence of treatments within particular strategies. When the objective function was set to maximize the production of net energy, the alternate financial "objective" can be used as a constraint. This may be set as an expected lower limit for net earnings, or an upper limit on acceptable losses, or as an unbounded constraint that simply calculates the net financial return from the land brought into solution. Conversely, the objective function can be established to maximize net returns (or minimize loss) while subjecting the system to an energy "constraint." Again, the constraint may be set as a lower limit to net energy returns, an upper limit to energy losses, or an unbounded constraint that calculated the net energy return from the optimal financial strategy.

Various silvicultural and managerial treatments were entered as requirements within a particular strategy and sequenced at particular points in time. A series of linkage constraints required that any hectare of land employed in a given strategy received all of the treatments in the strategy and in proper order over time. This constraint provided for an evaluation of all treatments within each strategy while requiring the selection of an optimal strategy that maximizes the objective function.

The volume of land available for any particular strategy was also entered as a constraint. The area used in the model, 924 ha, constitutes a viable working unit for a commercial-sized biomass system determined by equipment

operations for a given task and other plantation establishment time constraints.

In certain instances, equations were created that do not serve as bounded constraints except for their being set greater than or equal to zero. These statements take on an accounting function and track the usage of certain inputs, such as fertilizers and cost input (financial or energy). At the completion of the problem run, they identified total usage of the resource and their source of consumption.

Structure of the Basic LP Model

The relations (linkages not included) used in the LP model for identifying a commercial-sized, short-rotation biomass plantation system were as follows:

1) Objective function as net return (financial or energy)

$$\text{MAX } Z = \sum_{i=1}^{4} \sum_{j=1}^{2} \sum_{k=1}^{4} \sum_{l=1}^{15} C_{ijkl} X_{ijkl}$$

i = the year of employment within the 4-year rotation
j = the soil type, Basher (1) or Morrison (2)
k = the management strategy, control (1), fertilization (2), irrigation (3), or fertilization/irrigation (4)
l = silvicultural or management treatments (1-14) and the output generated from the system (15)

Subject to

2) Land constraints

$$\sum_{i=1}^{1} \sum_{j=1(2)}^{1(1)} \sum_{k=1}^{4} \sum_{l=m}^{m} A_{ijkl} X_{ijkl} = \text{ha}$$

The land constraints represented a series of eight constraints employed in the first year of the four-year rotation (i=1). There were four constraints per soil type (j=1, j=2), and they existed for each strategy (k=1-4). Since the areal determination for a commercial-sized plantation was based on a viable working unit, then "l=m" was necessary, where "m" equaled some treatment (1-14) most binding on the system. The land constraints in conjunction with the linkages, guaranteed that 924 ha have undergone all treatments within the optimal strategy.

3) Cost constraints

$$\sum_{i=1}^{4} \sum_{j=1}^{1} \sum_{k=1}^{1} \sum_{l=1}^{14} A_{ijkl} X_{ijkl} \geq 0$$

$$\vdots \qquad\qquad \vdots$$

$$\sum_{i=1}^{4} \sum_{j=2}^{2} \sum_{k=4}^{4} \sum_{l=1}^{14} A_{ijkl} X_{ijkl} \geq 0$$

There were eight cost constraints in the model to tabulate the total cost (l = 1-14) for a strategy (k-l=4) and site (j=1-2) chosen as the optimal strategy. It represented the total cost over the entire rotation (i=1-4).

4) Alternate net return (financial or energy) or optimal solution

$$\sum_{i=1}^{4} \sum_{j=1}^{1} \sum_{k=1}^{1} \sum_{l=1}^{15} A_{ijkl} \; X_{ijkl}, \text{ unbounded}$$

$$\vdots$$

$$\sum_{i=1}^{4} \sum_{j=2}^{2} \sum_{k=4}^{4} \sum_{l=1}^{15} A_{ijkl} \; X_{ijkl}, \text{ unbounded}$$

The above represented eight unbounded constraints under each analysis (financial or energy). If the model was run to optimize the net energy, the alternate net return delivered the financial net return of that strategy. Conversely, the net return for energy was reported for the optimal financial strategy.

RESULTS AND DISCUSSION

Task 1 - Establish Plantation

Short-rotation hybrid poplar plantations are analogous to the production of row crops. Results from this project have expanded the estimated plantation establishment energy inputs reported by Bowersox and Blankenhorn (1979) by measuring actual biomass yields as a function of management strategy and site. Proper site preparation is critical to successful plantation establishment and resultant yields. This project has carefully evaluated site preparation operations as well as all other operations essential to plantation establishment.

Energy values and equipment operation time from the actual site preparation of small experimental plots were higher than anticipated in full scale plantations because of increased turning and idle time. However, the establishment of small experimental plots permitted an identification of the necessary field operations required in each phase of work. Time and operational constraints, in part based on an extrapolation of small scale to large scale systems, were used to develop financial and energy values for a commercial-sized operation.

Site Preparation and Weed Control

Plowing and disking prior to planting were the only weed control measures in the plantation treatment units established in 1980. Weed growth in these replications was a major problem and the weeds ultimately retarded the tree growth in the first year. Chemical weed control was not possible in the 1980 replications because of limited knowledge on safe herbicides for *Populus* hybrids. After identifying the weed species on the Morrison and Basher sites, a variety of specialists were consulted and the 1981 weed control program was started late in the summer of 1980.

The first step in the weed control strategy was to remove as many of the weed species as possible using total kill herbicides. In August 1980, glyphosate at 2.24 kg/ha active ingredients (a.i.) and dicamba at 3.36 kg/ha a.i. were used at the Basher site and glyphosate was used at 2.24 kg/ha a.i. at the Morrison site. The second phase of the weed control strategy was to develop a potentially successful pre-or post-emergence herbicide procedure for use at planting time.

The approach used to develop a potentially successful chemical weed control program was as follows:

1. The first step was the establishment of a reasonable weed control objective. There would be a major difference in strategies seeking 100% control of all weed species between May and September or 70% control of the most important weed species between May and July.

2. The next step was the determination of the weed species to be controlled. The dominating herbaceous communities present on the site before site preparation needed to be evaluated. In addition, activities such as site preparation, soil fertility adjustments,

irrigation and so forth may create the conditions favorable for a different community of weed species. Evaluation of existing and invading weed species needed to be controlled was completed during the 1980 growing season.

3. The third step was to consult specialists with knowledge of associated weed, soil, climatic and cultural interrelationships. Recommendations of potential herbicides from the specialists included not only chemicals to control the weed species but also an awareness of potential impact of these chemicals on the trees.

4. Develop a set of herbicides that were compatible with tree growth and possessed the potential to control the expected weed species.

5. The next step was to determine the potential impact of the herbicides on the trees by applying the herbicides to soils, from the site, containing planted trees. The effect of the herbicide on the weeds was known, but in most cases, the effect of the herbicide on the trees was unknown. One, two and four times the recommended application rates were used to account for any variability in the field application of the herbicides.

6. After accepting an herbicide strategy, adherence to application instructions was essential.

Potential pre- and post-emergence herbicides were screened in greenhouse studies conducted between January and April 1981. These studies, three separate trials, were conducted with soil collected from each plantation site and included seven chemicals reported to control expected Basher and Morrison 1981 weed species. The objective of this screening was to evaluate the effect of the chemicals on the developing root and shoot tissues of the trees. Herbicides* tested in these greenhouse trials were: (1) devrinol (napropamide) at 8.97 to 35.88 kg/ha a.i., (2) dual (metalachlor) at 3.36 to 13.44 kg/ha a.i., (3) goal (oxyfluorfen) at 1.12 to 4.48 kg/ha a.i., (4) lorox (linuron) at 0.56 to 2.24 kg/ha a.i., (5) modown (bifenox) at 2.24 to 8.96 kg/ha a.i., (6) prowl (pendimethalin) at 1.68 to 6.72 kg/ha a.i. and (7) ronstar (oxadiazon) at 4.48 to 17.92 kg/ha a.i.

From these screening trials, a weed control strategy was developed for each site that would provide 80% (dry weight basis) control of the weed community until July 1. It was assumed that if the plantations were at least 80% weed-free by this date, weed competition would not limit tree growth. The herbicide programs were:

a. Basher site - a pre-emergence herbicide to control nutsedge (metolachlor at 3.36 kg/ha a.i.) plus a pre-emergence to control

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*The trade or brand names mentioned in this publication are supplied with the understanding that no discrimination is intended, and no endorsement by the School of Forest Resources at The Pennsylvania State University is implied. Furthermore, in some instances, the same compound may be sold under different trade names and carry different label clearances. It is the user's responsibility to follow the label.

other grass, grasslike and broadleaf weeds (oxyfluorfen at 1.12 kg/ha a.i.).

b. Morrison site - a pre-emergence herbicide to control grass and grasslike weeds (napropamide at 8.97 kg/ha a.i.).

Ocular estimates of the weed communities at both sites on July 1, 1981 indicated that 90% or more of soil surface was free of herbaceous vegetation. Late growing season inventories of oven dry herbaceous vegetation were conducted to determine the amount of herbaceous vegetation growing in the 1981 planted replications (four 1.0 m^2 plots per 1981 replication-site-treatment unit) and these were compared to six 25.0 m^2 native herbaceous vegetation plots at each site. These native vegetation plots were adjacent to the Populus replications.

The species of weeds that collectively accounted for 90% or more of the herbaceous vegetation growing in the native vegetation plots are presented in Appendix A (Table A-1). At the Basher site these species plus all other weeds produced a total of 280.0 g OD biomass/m^2, with 45.1 g/m^2 as grass and grasslike vegetation and 234.9 g/m^2 of broadleaf weeds. These values were significantly greater than the 12.4, 177.7 and 190.1 g/m^2 of oven dry grass (and grasslike), broadleaf and total herbaceous growth, respectively, produced at the Morrison site.

A similar inventory of herbaceous vegetation was conducted on the Populus replications planted in 1981. Average OD weights of grass (and grasslike), broadleaf weeds and total herbaceous vegetation by site and treatment were determined and are presented in Appendix A (Table A-2). Total OD herbaceous plant growth on the Morrison site of 29.8 g/m^2 was significantly lower than the total herbaceous vegetation at the Basher site (63.7 g/m^2). The reason for this difference was the significantly greater amount of oven dry grass (and grasslike) vegetation (mainly nutsedge) at the Basher site. There were no significant differences in the amount of oven dry herbaceous vegetation among the Populus management strategies at the Morrison site. At the Basher site, irrigation resulted in significantly more broadleaf vegetation, fertilization had significantly lower total weeds and the fertilization/irrigation increased the amount of oven dry grass (and grasslike) vegetation. Overall, the herbicides applied in spring 1981 reduced the weed growth in the Basher Populus plots by 77%, compared to the potential herbaceous growth of 280.0 ODg/m^2, and at the Morrison site, the herbicides reduced the weed growth in the Populus plots by 84%, compared to the potential herbaceous growth of 190.1 ODg/m^2.

Net result of the weed control program can be seen in the first year total height growth of the 1980 and 1981 planted trees in Figure 5. The "normal" line is an average of first growing season total height growth from four plantations of Populus hybrid NE-388 (planted between 1966 and 1971) where weed competition was controlled by hand hoeing or black polyethylene mulch. None of these previous plantations were fertilized or irrigated. The 1980 planted control trees averaged 0.76 m on September 5 and the 1981 planted control trees averaged 1.43 m on August 28. The "normal" weed free height would have been 1.20 m on September 1 (Figure 5).

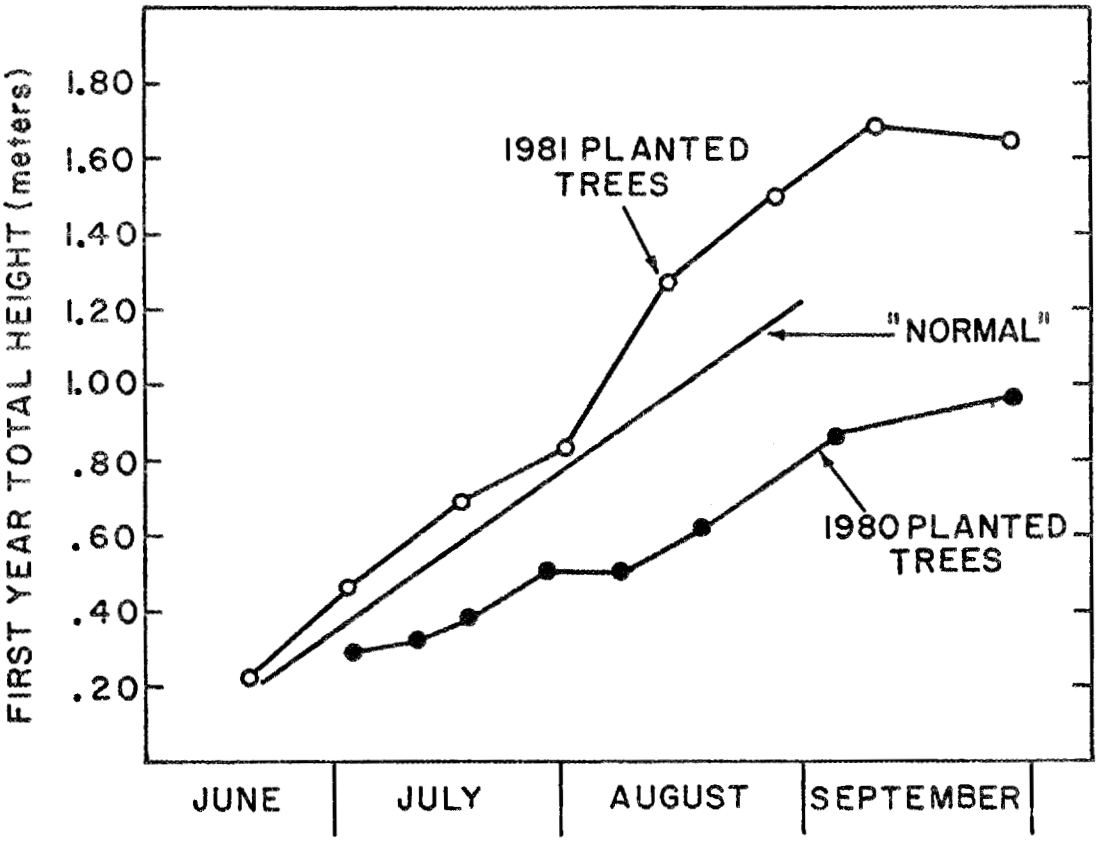

Figure 5. First year total height growth for Populus hybrid NE-388.[1/]

[1/] Total height values for the 1980 and 1981 planted trees are based on 240 trees per year. The "Normal" line is based on averages from more than 1000 trees from four other plantations of NE-388 planted on a variety of sites in central Pennsylvania between 1966 and 1971 that had completed weed control by either mechanical cultivation or black polyethylene mulch. These previous plantations were not fertilized or irrigated.

Value of the effective weed control program for the 1981 planted trees had carryover to the second growing season. Lack of an effective establishment year weed control program for the 1980 plantings resulted in control treatment trees averaging 1.69 m in height and 1.40 cm in diameter at two years of age. In comparison, the 1981 control treatment trees averaged 4.3 m in height and 2.80 cm in diameter at the end of two growing seasons.

Management Strategies - Fertilization

The fertilization treatments were designed to obtain a balanced soil nutrient status promoting initial survival and tree growth. Fertilization recommendations to yield 47 ODt of *Maize* silage per hectare (field weight) were used to develop the fertilization program and to achieve these nonlimiting conditions.

Soil testing results for the replications established in 1980 and 1981 are presented in Appendix A (Table A-3). Initial fertilizer amounts for the 1980 and 1981 plantings are presented in Table 1-1.

Survival - The rates of N, P, K, Ca and Mg applied to the Basher silt loam and the Morrison sandy loam soils did not appear to improve tree survival during the establishment phase. At regular intervals in the initial growing seasons, measurements of tree survival were made on 17 randomly selected, completely independent by observation date, trees per site-replication-treatment. During establishment, the percentage of surviving trees greater than 0.1 m tall ranged from 78 to 98% (90% average) for the controls and 69 to 98% (87% average) for the fertilized trees (Appendix A, Tables A-4, 5). Average survival for the six fertilization replications (1980 and 1981 combined) at each site was about 86% at the end of the first growing season (Table 1-2). These estimates were based on 3264 planted continuous inventory trees (2 sites x 6 replications x 272 trees per site per replication). The average survival at the end of the first growing season for all control trees was 86%.

Height - The fertilization program used in this study did not improve total tree height during the establishment year, except for late in the 1980 growing season (Appendix A, Tables A-6, 7). In the 1980 planted replications with inadequate weed control, a sustained significant total tree height growth advantage for the fertilized trees over the control trees was first recorded at the Basher site on August 19 and after September 5 at the Morrison site. In the 1981 planted replications with excellent weed control total tree height growth values for the control and fertilized trees were equal on both sites.

The one year old total height of all 1980 planted trees averaged 0.94 m at the Basher site and 0.98 m at the Morrison site (Table 1-3). For the 1980 planted trees, the control total height averaged 0.70 m at the Basher site and 0.87 m at the Morrison site. For the 1981 planted trees, the fertilized trees averaged 1.69 and 1.56 m for the Basher and Morrison sites, respectively, and the control trees averaged 1.63 and 1.72 m for the Basher and Morrison sites, respectively (Table 1-3). Combined over year of establishment, the average one year old total height was 1.23 m for the controls and 1.41 m for the fertilized trees (Table 1-3).

Table 1-1. Amount of fertilizer and lime applied at time of establishment for the 1980 and 1981 planted trees, by plantation site.

Plantation Site	N[1/]	P_2O_5[2/]	K_2O[3/]	Lime[4/]	Mg[5/]
	kg/ha				
Basher					
1980	179	179	179	3093	0
1981	169	114	189	4343	86
Morrison					
1980	179	179	202	6120	146
1981	169	134	168	4762	151

[1/] Broadcast application of ammonium nitrate at 33% N in May, after bud break.

[2/] Applied as triple superphosphate at 46% P_2O_5 before planting, and disked into soil.

[3/] Applied as potassium chloride at 60% K_2O before planting, and disked into soil.

[4/] Applied as ground limestone with minimum CaO of 51% and $CaCo_3$ equivalent of 92.28%.

[5/] Applied as ground dolomitic limestone with a minimum Mg of 3%, minimum CaO of 44% and $CaCO_3$ equivalent of 89% for the 1980 applications. Specifications for the 1981 applications were a minimum MgO of 11%, minimum CaO of 35%, and $CaCO_3$ equivalent of 89% for the 1981 applications.

Table 1-2. Average survival[1/] of one through four year old trees for the 1980 and 1981 planted trees, by plantation site and treatment.

Plantation Site	Treatment	Age 1	2	3	4
1980 Planting		- - - - - - - - - -	%	- - - - - - - - - -	
Basher					
	Control	84	87	84	82
	Irrigation[2/]	86	88	86	84
	Fertilization	81	81	78	71
	Fertilization/ Irrigation[2/]	82	80	79	72
Morrison					
	Control	88	91	90	89
	Irrigation[2/]	82	83	80	79
	Fertilization	80	79	78	76
	Fertilization/ Irrigation[2/]	80	79	79	78
1981 Planting					
Basher					
	Control	91	91	89	87
	Irrigation	91	91	90	90
	Fertilization	97	97	96	82
	Fertilization/ Irrigation	93	92	93	79
Morrison					
	Control	90	91	91	91
	Irrigation	86	85	85	85
	Fertilization	84	85	85	82
	Fertilization/ Irrigation	85	86	85	81

[1/] Survival was based on the total number of 272 trees planted per site-treatment-replication that were alive and greater than 0.1 m tall. There were 3 replications planted in 1980 and 3 replications planted in 1981.

[2/] Trees were not irrigated in the first growing season only.

Table 1-3. Average total height and stem diameter at 15 cm above ground of one through four year old trees for the 1980 and 1981 planted trees, by plantation site and treatment.

Plantation Site	Treatment	Total Height[2/] (by Age) 1	2	3	4	Diameter[2/] (by Age) 1	2	3	4
		- - - - meters - - - -				- - - - - - cm - - - - - -			
1980 Planting									
Basher									
	Control	0.7a	1.9b	4.1b	5.4ab	0.6a	1.5b	2.7b	3.5b
	Irrigation[3/]	0.8b	2.6c	4.9c	6.2c	0.7b	2.0c	3.2b	4.0c
	Fertilization	1.2d	3.5e	5.7d	7.4e	0.9d	2.5e	3.7cd	4.6e
	Fertilization/ Irrigation[3/]	1.1c	3.7f	5.8d	6.9d	0.9c	2.7f	3.8d	4.6e
Morrison									
	Control	0.9b	1.6a	3.9a	5.2a	0.7b	1.4a	2.4a	3.3a
	Irrigation[3/]	0.7a	1.5a	4.0ab	5.6b	0.6a	1.4ab	2.7b	3.6b
	Fertilization	1.2d	3.4d	5.8d	6.9d	0.9c	2.4d	3.6c	4.2cd
	Fertilization/ Irrigation[3/]	1.1c	4.0g	5.9d	7.0d	0.9c	2.7f	3.7cd	4.4de
1981 Planting									
Basher									
	Control	1.7bc	4.2b	5.6b	6.8a	1.4b	2.7b	3.6ab	4.2a
	Irrigation	1.6a	3.7a	5.3a	6.7a	1.3a	2.5a	3.5a	4.1a
	Fertilization	1.7c	4.5c	5.7c	7.1b	1.3b	3.0cd	4.0c	4.8c
	Fertilization/ Irrigation	1.9d	4.7d	6.0cd	7.4c	1.5c	3.2de	4.1cd	4.8c
Morrison									
	Control	1.7c	4.6cd	5.8bc	6.7a	1.4b	3.0c	3.7b	4.2a
	Irrigation	1.7c	4.6cd	6.0de	6.9ab	1.4b	3.1de	4.0cd	4.6b
	Fertilization	1.6ab	4.7d	5.9cd	7.1b	1.3a	3.1cd	3.9c	4.6b
	Fertilization/ Irrigation	1.7c	4.7d	6.2e	7.4c	1.4b	3.3e	4.2d	5.0d

1/ Means of 3 replications for 1980 and 1981 data. Treatment means within and between plantation sites - by planting year - with common letter for each diameter or height set were not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance.

2/ Diameter and total height values were averages of 100 randomly selected trees per site-treatment-replication.

3/ Trees were not irrigated in the first year only.

Diameter - The one year old diameter (at 15 cm above ground) values indicated a control-fertilization-year of establishment pattern similar to total tree height values (Table 1-3). Fertilized trees were larger than the controls for the 1980 planted trees, but no apparent difference was evident in the 1981 planted trees. Combined over sites and years of establishment, the 15 cm above ground diameter for all surviving continuous inventory one year old trees averaged 1.00 cm for the controls and 1.10 cm for the fertilized trees.

First Growing Season Fertilization Summary - Fertilization did not have an effect on the initial year survival. Fertilization investments for situations lacking adequate weed control resulted in trees that were taller and larger in diameter than nonfertilized trees. However when the potentially competitive weed community was successfully excluded, fertilization did not increase the first growing season tree height or stem diameter. Hence, management strategies may be able to reduce or eliminate these costly amendments, particularly nitrogen.

Management Strategies - Irrigation

This treatment was designed to maintain a soil moisture condition that would enhance plantation establishment and development. Maintenance of soil moisture above the 50% available water level was selected as a non-limiting condition. Irrigation was cancelled in 1980 because of funding delays and problems in developing a well at the Morrison site. In 1981 a trickle irrigation system was installed at each site. This system was selected because of the high degree of experimental control, minimum water loss due to evaporation and low pumping pressures.

The Basher site required about a 3.0 m vertical water lift from an adjacent stream with a pumping pressure of 69 kPa; the water table here was less than 1.0 m deep. A well was installed at the Morrison site and water was lifted about 65 m from the water table to the soil surface. Irrigation water first passed through a control center where the water was filtered and control over the water pressure and volume was maintained. The water then flowed through 5 - 6.5 cm trunk lines to a 5 cm header with 43 emmitter lines (each line was 29.4 m long) which were used to trickle the water onto the plots. The emitter lines (biwall tubing) were placed 0.4 m apart and had orifices every 30.6 cm. The system was operated at a design pressure of 70 kPa. This pressure produced a 30 cm stream of water (above ground) from each emitter line. At these rates, the irrigation system would amend each plot with 5768 ℓ/h which is equivalent to an approximate rainfall of 0.1 cm/h. The amount of water added to each plot was controlled to the nearest 5 ℓ and the water pressure was controlled to the nearest 3 kPa. No overland flow or erosion was observed during any of the irrigation cycles.

The need for irrigation increased when the weekly rainfall was below 2.5 cm or the average weekly maximum temperature was greater than 26°C. Two rain gauges were used to measure the daily rainfall at each site. Daily air temperatures were recorded on a hydrothermograph located in a standard weather station shelter at each site. Average weekly maximum and minimum temperatures and weekly rainfall values for the 1981 growing season were recorded (Appendix A, Table A-8).

Soil moisture characteristics for each plot were determined from field measured dry soil bulk density and amount of water in the soil at field capacity (100% available water level) tests. Amount of water in the soil at 15 atm was determined from published values (USDA 1978) and verified by the soil characterization laboratory at the Pennsylvania State University. Amount of water (kg/m^3 or % OD weight) at 0, 50, 75 and 100% available water for each plot was determined. Soil moisture characteristics and available water level values were determined (Appendix A, Tables A-9, 10).

When the weather conditions indicated an increase in the possible need for irrigation, the soil moisture levels in the irrigation plots were measured on a daily basis. Soil moisture in the upper 20 cm was measured at three random points within the continuous inventory trees. These observations were compared to the individual plot soil moisture characteristics and the amount of irrigated water needed on each plot was determined. When monitor equipment failed, standard agronomic indicators of water stress were used to determine irrigation needs. The 1981 weather conditions and irrigation amounts are summarized in Table 1-4.

Initially, irrigation on each plot was started when the soil moisture levels approached the 50% available water level. This strategy included ranking the irrigation plots on a master schedule and resulted in relatively long irrigation times per plot. Delays in securing irrigation water on all 24 treatment units (irrigation-12 and fertilization/irrigation-12) per site permitted some units to approach the 50% available water level. After the first cycle, treatment units were scheduled for irrigation as they approached the 75% available water level.

Irrigation was attempted at the Morrison site (Appendix A, Table A-12) on July 16, but a pump failure and rain delayed full scale operation of the irrigation system until August 5, 1981. Full scale operation of the irrigation system on the Basher site (Appendix A, Table A-11) began on July 18 but was interrupted by 6.3 cm of rain on July 20-21. Irrigation at both sites was resumed on August 5 and continued until August 28. Rain from August 31 to September 6 terminated the irrigation program for 1981.

Survival - Irrigation treatments on the Basher silt loam and the Morrison sandy loam soil of this study did not appear to improve the within growing season survival rates of trees planted in 1981. Survival was based on the number of trees greater than 0.1 m in height measured on 17 randomly selected, completely independent by observation date, trees per site-replication-treatment at eight intervals in the first growing season. Irrigation survival values ranged from 74 to 98% (average of 88%) and these values were similar to the controls (range of 82-98%, average 91%) and the fertilization (range of 68-98%, average 88%) values given in Appendix A (Tables A-4, 5). Percentage survival of the end of the first growing season for the three 1981 planted irrigation replications at each site averaged 91% for the Basher site and 86% at the Morrison site (Table 1-2). Average survival on the Basher and Morrison sites for the 1981 controls was 91 and 90%, respectively, and for the 1981 fertilized trees was 97 and 84%, respectively.

Height - The influence of the irrigation program used in this study on total tree height growth during the establishment year of 1981 was minimal

Table 1-4. Monthly summary of weekly maximum and minimum temperatures, rainfall and irrigation for the Basher and Morrison plantation sites in 1981.

Site-Measurement	June	July	August
Basher			
Temperature[1/] (C°)			
Weekly Minimum	13.6	14.1	12.8
Weekly Maximum	26.2	27.4	25.6
Rainfall[1/] (cm)	13.4	7.9	4.9
Irrigation[2/] (cm)	0.0	1.7	5.9
Morrison			
Temperature[1/] (C°)			
Weekly Minimum	14.0	14.6	13.5
Weekly Maximum	24.7	27.2	25.6
Rainfall[1/] (cm)	13.2	7.6	4.4
Irrigation[2/] (cm)	0.0	0.0	8.0

[1/] Average weekly values are presented in Appendix A.

[2/] Amount of water added to individual plots, by treatment, site and date, are presented in Appendix A.

compared to all other treatments on both sites. The establishment year elongation values, by treatment site and dates, are presented in Appendix A (Tables A-6, 7). The maintenance of soil moisture above the 50% available water level did not produce a sustained significant difference in one year old total tree height (Table 1-3). Total height of the surviving one year old 1981 planted trees for the irrigated continuous inventory trees on both sites averaged 1.62 m. The one year old total height of the 1981 planted trees of the control continuous inventory trees averaged 1.68 m and the fertilized trees averaged 1.63 m for both sites.

Diameter - Diameter growth on the irrigated plots was not evaluated during the growing season. But similar to the irrigated one year old total tree height values, stem diameter of the irrigated trees at the end of the first growing season did not appear to have much enhancement over control or fertilization. On both sites, the control, irrigated and fertilized trees planted in 1981 had average diameters at 15 cm above ground of 1.37, 1.33 and 1.30 cm, respectively (Table 1-3).

First Growing Season Irrigation Summary - Trees planted in 1980 were not irrigated. It should be noted that the 1981 trees were planted by mid-April and the abundant rain and relatively cool temperatures until July were favorable for tree establishment. Also, weed control during the 1981 growing season was excellent. Late planting dates, drought, and high temperatures or poor weed control may have produced different results. In any event, irrigation did not seem to improve the first growing season height, diameter or survival values compared to control and fertilization values.

Management Strategies - Fertilization/Irrigation

This treatment was designed to maintain the combined non-limiting soil nutrient and soil moisture conditions for the plantations during the establishment period. Procedures described for fertilization and irrigation were combined for this treatment. Data on the soil nutrient status before planting, soil moisture characteristics and amount and frequency of irrigation for the fertilization/irrigation treatment units are presented in Appendix A (Tables A-3 and A-8, 9, 10, 11, 12). Amount of fertilizer and lime added at the beginning of the growing season is given in Table 1-1. A summary of the total water added is given in Table 1-4.

Survival - The combined effects of fertilization and irrigation improved the survival rates for the trees planted in 1981 in the Basher silt loam and the Morrison sandy loam soil. Periodic estimates of establishing tree survival (Appendix A, Tables A-4, 5) ranged from 76 to 96% (average of 89%) and were similar to the controls (range of 82-98%, average 91%), fertilization (range of 68-98%, average 88%), and irrigation (range of 74 to 98%, average of 88%). Averaged over both sites, the one year old survival for the three fertilization/irrigation replications planted in 1981 was 89%. Averaged over both sites, the control, irrigated and fertilized 1981 planted one year old survival rates were 90, 89 and 91%, respectively (Table 1-2).

Height and Diameter - The fertilization/irrigation treatments resulted in one year old trees that were slightly greater in average total height but

there was no treatment advantage in the stem diameter values, as compared to all other treatments. The one year old Basher and Morrison fertilization/irrigation trees were 1.78 m in height compared to 1.68 m in height for control, 1.63 m in height for irrigation and 1.63 m in height for fertilization trees (Table 1-3). Diameter at 15 cm above ground for the one year old trees averaged 1.37, 1.33, 1.30 and 1.42 cm for the control, irrigation, fertilization and fertilization/irrigation trees, respectively (Table 1-3).

First Growing Season Fertilization/Irrigation Summary - These results, as well as the results for the fertilization and the irrigation treatments, suggest that native site fertility and normal rainfall are adequate for tree survival, total height and diameter growth in the establishment phase given similar weather, planting dates, weed control, site, tree parentage and spacing conditions. However, in less than ideal situations the combined fertilization/irrigation strategy may result in substantially better plantation establishment than the other management strategies.

Plantation Establishment Financial and Energy Analyses

Equipment Operation - The scenario for plantation establishment year operations included: 1) Fall Preparation - total kill herbicide, mower-conditioner and offset disk, 2) Spring Planting - disk harrow, planting, pre-emergence herbicide and fertilizer spreading and 3) Growing Season - insecticides and fungicides. This particular scenario is based on the constraints associated with cultural requirements and their optimal period for application, the total time frame available for the individual operations and the rate of production for accomplishing each operation.

Analysis of the plantation establishment operations indicated the offset disk was the critical constraint on the amount of land that could be cultivated in the fall preparation phase. An offset disk (3.7m in width) pulled by a 170 hp tractor at 60% field efficiency and 9.7 km/ha could prepare 924 ha of land over an 11 week period. The offset disk followed two 70 hp tractors that were spraying (total kill herbicide) and mowing. Using 924 ha as the base working unit, the spring planting operations would again make use of the two 70 hp and one 170 hp tractors for disk harrowing, planting, fertilizer spreading and spraying pre-emergence herbicides. The number of tractors used and length of time each tractor was used for each operation were determined by the time frame available for the operation and the field capacity (ha/h) of the various equipment units. Table 1-5 provides a summary of the plantation establishment year operations and the time allotted to each operation.

Implement Capacity - The methodology for establishing the number of hectares prepared per year for a given implement was: 1) establish an areal rate of productivity, or field capacity, 2) calculate power requirements and 3) develop energy requirements per hour and per hectare. The above methodology was further complicated by the ranges in equipment size, power requirements, speed of performance and typical field efficiency. (Field efficiency indicates what percentage of land could be prepared considering factors such as terrain and size of fields). The typical field efficiencies listed in Appendix A, Table A-13 (Waters and Daum 1974) are for farm implements used on good agricultural fields. This

Table 1-5. Schedule of annual operations for establishing a 924 ha plantation.

Implement	Time Frame	Total Weeks	Total Operating Hours
Fall Preparation			
1) Sprayer (total kill herbicide) 1 - 70 hp tractor	Aug. - mid Sept.	7	143
2) Mower Conditioner 1 - 70 hp tractor	Aug. - Sept.	9	350
3) Offset Disk 1 - 170 hp tractor	mid Aug. - Oct.	11	440
Spring Planting			
1) Disk Harrows 2 - 70 hp (200 h each) and 1 - 170 hp (40 h) tractor	mid Mar. - mid Apr.	5	440
2) Planters[2/] 4 - 70 hp (343 h each) and 1 - 170 hp (343 h) tractor	Apr. - mid May	7	1715
3) Sprayer (pre-emergence herbicide) 1 - 70 hp tractor	mid May - mid June	5	143
4) Spreaders (fertilizer)[3/] 2 - 70 hp (203 h each) and 1 - 170 hp (203 h) tractor	mid May - mid June	5	609
Summer Growing Season			
1) Sprayer (insecticides) 1 - 70 hp tractor	mid June - July	3	143
2) Sprayer (fungicides) 1 - 70 hp tractor	mid June - July	3	143

[1/] Based on data presented in Appendix A, Tables A-13, 14.
[2/] Based on a 49 hour week.
[3/] Machinery operations associated with fertilization strategies.

procedure established the constraints the equipment placed on the plantation size.

Discussions with agricultural engineers and farm managers indicated the lower value for the field efficiency (field efficiencies on good agricultural fields - Appendix A, Table A-13) should be decreased by 50% and the upper value by 33.3% for use of farm implements on old (abandoned) agricultural fields. It was reasonable to assume that biomass plantations would be grown on old rather than good agricultural fields. Therefore, the upper value for field efficiency on old agricultural fields established the inputs to the LP model. Also, maximum implement width of 3.7 m was used for the offset disk and the disk harrow, with a required maximum tractor power take off of 140 hp. The maximum implement width of 3.7 m reduced the need for truck transportation of implements.

Field capacity was the amount of land an implement could prepare in an hour and was calculated as:

Field capacity (ha/h)

$$= \frac{\text{speed (m/h) x implement width (m) x fractional field efficiency}}{(10{,}000\ \text{m}^2/\text{ha})}$$

Power requirements were calculated as:

$$\text{Drawbar hp} = \frac{\text{draft (pounds) x speed (mph)}}{375}$$

and

$$\text{Power Take Off hp} = \text{Power (hp/m) x width (m)}.$$

Fuel consumption calculations were based on diesel powered tractors due to their improved delivery of 13 hp-h/gallon diesel fuel versus 9 hp-h/gallon gasoline for gasoline powered tractors (McCurdy 1975). The diesel fuel consumption was estimated as (Waters and Daum 1974):

$$\frac{\ell}{\text{h}} = \text{hp} \times 0.05\ \frac{\text{gal diesel}}{\text{hp-h}} \times 3.785\ \frac{\ell}{\text{gallon}}.$$

Based on the power take off requirements for 60 and 140 hp, the tractor sizes needed for plantation establishment preparations were 70 and 170 hp using 13.2 and 32.1 ℓ/h of diesel fuel, respectively. Appendix A (Table A-14) lists field capacity (ha/h) for selected implements used in establishing and maintaining the plantations.

Planting Populus hybrids differs sufficiently from other agricultural planting systems to warrant a production analysis specific to its system. By referencing studies on the planting of Populus hybrid an estimate was obtained on the field capacity of planting units and the number of planting units required for planting 924 ha in a 7 week time frame.

According to Cram (1974) two 4 row planters, each utilizing a crew of 10, were able to plant 155,000 cuttings (at a 1 x 1 m spacing), in an 8-hour day. This was equivalent to 9687.5 cuttings per hour per planting unit. In the work at Rhinelander, Wisconsin, Hansen et al. (1981), reported a planting

rate of 5,000 cuttings/h for a 4 row mechanical planter. Based on these rates it was considered reasonable to envision 7,500 cuttings/h for a 4 row planter or 1875 cuttings/row/h. Since these previous rates were based on a 1 m spacing between rows, a modification was proposed for this study -- the 0.8 m row spacing and a 6 row planter. Using the per row rate of 1875 cuttings/h the 6 row planter could plant 11,250 cuttings/h.

With an 0.6 by 0.8 m spacing, 20,833 cuttings/ha could be planted. For a 924 ha plantation 19,250,000 cuttings must be planted. Since a planting unit would operate during a time frame of 7 weeks (April 1 to mid-May) on a 5 day - 10 h/day basis, this provided 350 h of operation. With a production rate of 11,250 cuttings/h, one unit could plant 3,937,500 during the 7 week time frame. As such, planting 19.25 million cuttings for the entire 924 ha plantation would require 4.88 planting units. By using 5 planting units, each unit could work a reduced assignment of 343 h during the 7 week time frame. For purposes of the financial model it was assumed that the company would own and operate three of the planting units, own the remaining two 6 row planters but subcontract the tractor services and labor on the latter 2 units.

The field capacity of a 6 row planting unit was calculated by multiplying the number of cuttings planted/h (11,250) by their spacing (0.6 m by 0.8 m = 0.48 m^2) to establish the area planted in one hour (5400 m^2). This represented a field capacity of 0.54 ha/h.

Equipment Manufacturing and Repair Energy - An accounting convention for developing the total energy associated with a piece of farm machinery was given in Pimentel (1980). This method divided the energy associated with farm machinery into three categories: 1) energy embodied in the materials, 2) energy associated with manufacturing and fabricating the equipment and 3) energy associated with repair parts. Since it was impossible to follow the production of a piece of machinery from its inception as crude ore through steel making, etc., certain averages were used to establish the baseline energy inputs.

Embodied energy was calculated by multiplying implement weight by 15,000 kcal/kg for steel, 20,500 kcal/kg for tires and 11,814 kcal/kg for tractors. Fabrication energy was calculated by multiplying the weight of the implement by 3,494 kcal/kg for tractors, 2,061 kcal/kg for plows, offset disks and planters, 1,995 kcal/kg for disk harrows and 1,764 kcal/kg for sprayers, spreaders and mowers. The sum of the embodied and fabrication energy was multiplied by 0.82. This assumed its reliable or functional life was 82% of its total life (Pimentel 1980). To estimate energy associated with repair parts, the sum of the embodied and fabrication energy was multiplied by 0.2967 for 170 hp tractors, 0.2474 for 70 hp tractors, 0.3083 for plows, offset disk and disk harrow, 0.2530 for planters and mowers, 0.3040 for fertilizer spreaders, and 0.3040 for sprayers. The total machinery energy costs equalled the sum of the embodied, fabrication and repair parts energy on a reliable life basis (Pimentel 1980). Equipment manufacturers were contacted to establish the characteristics of the implements. Appendix A (Table A-15) lists the manufacturing and repair energy values for the equipment used to establish and maintain the plantations.

Energy Cost Procedures - The total estimated energy costs for each implement and its tractor were converted to an hourly and per unit area energy cost by dividing the total estimated energy costs by the lifetime of the equipment in hours and, for the second measure, dividing this hourly cost by field capacity. For the equipment used in plantation establishment and maintenance the estimated life given in Doane's (1972) and Waters and Daum (1974) was: 1) tractor wear-out life - 12,000 h, 2) offset disk and disk harrow wear-out life - 2500 h, 3) fertilizer spreader wear-out life - 800 h, and 4) sprayer wear-out life - 1500 h, 5) planter wear-out life - 1200 h and 6) mower wear-out life - 1000 h.

The division of an equipment's total lifetime by its annual rate of usage identified the number of years in its total life. This latter value was needed for the subsequent calculation of financial depreciation. Appendix A (Tables A-16, 17) lists the energy consumption, hours of operation and expected lifetimes for the equipment used in establishing and maintaining the plantations.

Financial Cost Procedures - The basic division of financial costs for the commercial plantation were variable costs, those varying with the level of production, and fixed costs, constants not affected by the level of production. All cost estimates were based upon the previously proposed scenario for plantation establishment and maintenance (Table 1-5), with variable costs expressed on a per hour and per hectare basis. The fixed costs for individual implements were pro-rated over their proposed annual period of usage and were also expressed on a per h and per ha basis.

Fixed costs include insurance, shelter, depreciation and interest charges. Insurance estimates were secured through contacts with insurance companies (Wasson 1981) and amounted to an annual charge of 0.5% of the equipment's original list price. Annual shelter or housing costs for the equipment were based on agricultural engineering estimates (Waters and Daum 1974, Doane's 1979) and amounted to 1.0% of the equipment's list price. Depreciation and interest were treated as a fixed payment representing recovery of the original investment and an interest charge on the remaining principal. This was based on the formula:

$$R = \frac{V_o \times i \times (1 + i)^n}{(1 + i)^n - 1}$$

where R was the annual payment,
V_o, the original investment
i, the rate of return and
n, the years of indebtedness.

A variation was extended to the formula for the purpose of defining the hourly payment during an equipment's period of operation:

$$R \text{ (cost/hour)} = \frac{V_o \times i/h \times (1 + i/h)^{nxh}}{(1 + i/h)^{nxh} - 1}$$

where h was the annual hours of usage
and nxh would be the equipment's lifetime in hours (Appendix A, Table A-17).

Interest charges were based on an annual real rate of return of 5%. This particular rate represented a compromise between the 6% historic and projected after-tax real rate of return on U.S. corporate capital as reported by Klemperer (1979) and the 4% real rate proposed by Row et al. (1981) reflecting the current marginal long-term expectations for returns on new productive investments. The total costs for each piece of equipment are listed in Appendix A (Table A-18).

Variable costs included labor, fuel, repairs and maintenance. Labor costs considered the operation and numbers of employees working with a particular piece of equipment or assigned task. The following pay rates (Doane's 1981) were used in the various operations, with 5 to 20% added to the base rate for fringe benefits.

Operation	Base Pay Rate/h (less fringe)
Tillage	7.88
Planting	9.00
Mowing	8.25
Herbicide Application	9.00
Fertilizer Spreading	9.00
Planters (rate based on minimum wage)	3.35

Fuel costs were based on the hourly consumption of fuel for particular assignments (Appendix A, Table A-16). The fuel cost, as well as allied labor costs, were tied to the particular implement, rather than their tractor, to better reflect the specific labor and fuel usage for the combined implement and tractor in their operation. Repairs and maintenance were calculated as a proportion of the original purchase price and pro-rated over the equipment's lifetime in a manner recommended by American Society of Agricultural Engineers (1978). The total variable costs/h of equipment operation are reported in Appendix A (Table A-18), along with fixed costs and total hourly costs.

A comparison between the costs of owning the equipment and custom rates is presented in Appendix A (Table A-19). The cost of owning and operating the equipment was lower than the custom rates for the operations needed to establish the plantations (King, 1981). Table 1-6 summarizes the financial costs for equipment used in plantation establishment and maintenance for each operation. These data were used as inputs to the LP model in Task 3.

Nursery Establishment and Operation - Plantation establishment also included the establishment and operation of a nursery as a variable cost of the planting operation. Cuttings for planting would be harvested annually following a two year establishment period for the nursery. Operations for nursery establishment were the same as for plantation establishment. Commercial nursery operations could produce 250,000 (1.0 to 1.9 cm diameter) cuttings/ha/yr. If a wider range of cutting diameters was acceptable, yearly production could increase to 500,000 cuttings/ha. Based

Table 1-6. Financial costs for equipment used in plantation establishment and maintenance (924 ha/yr).

Implement (hp)	Annual Usage (h)	No. Units	Implement Total Cost $/h	Implement Total Cost ($)/h Including Tractor	Total Annual Cost ($)	Total Annual Cost ($) Including Tractor	% of Total Annual Cost Including Tractor
170 hp Tractor	1026	1	12.62		12948.00		
70 hp Tractor	2414	2	4.64		11201.00		
70 hp Tractor-Rental	684	2	4.64		3173.00		
Offset Disk-170 hp	440	1	22.60	35.22	9944.00	15496.89	10
Mower Conditioner-70 hp	350	1	19.92	24.56	6972.00	8596.00	6
Disk Harrow-70 hp	400	2	18.95	23.59	7589.00	9436.00	
170 hp	40	1	24.45	37.07	978.00	1482.80	7
Hybrid Poplar Planter-70 hp	1368	4	45.53	50.17	62285.04	68632.56	
170 hp	342	1	51.03	63.65	17452.26	21768.30	59
Fertilizer Spreader-70 hp	406	2	22.24	26.88	6479.76	8363.60	
170 hp	203	1	27.74	40.36	4358.41	6920.20	10
Herbicide Sprayer-70 hp	572	1	16.42	21.06	9392.24	12046.31	8

on a planting of 20,833 cuttings/ha (0.6 x 0.8 m spacing), a yield of 3 wands per stem and 5.3 cuttings per wand, the proposed nursery plantation would produce an average of 350,000 cuttings/ha/yr. This annual yield would commence at the end of the second growing season and continue until the end of the sixth year. A summary of the prorated establishment and annual maintenance costs is provided in Table 1-7.

The harvest of Populus hybrid wands would use a minimum of equipment and center on a three person crew cutting Populus hybrid wands with a brush-cutter power scythe at a projected rate equivalent to 21,600 cuttings/day. This system and its rate of production were confirmed through project field experience.

The operations of processing and packaging the cuttings were based on an indoor processing center employing three persons. Basically the conversion process involved cutting bundles of Populus hybrid wands into specified lengths with a band saw. A production rate of 12,000 cuttings/8 h day was confirmed by project personnel using a similar system.

Packaging involved placing 1400 cuttings in a 0.08 m^3 box, with 30% of the volume committed to a sawdust packing medium. One ha of plantation (20,833 cuttings) would use 15 boxes of cuttings, requiring a gross storage space of 1.7 m^3. A five month storage period was considered in the model.

Under this production model, a thousand cuttings cost $27.43 or 114.37/$10^3$ kcal. The division of major financial costs was: establishment of the nursery plantation - 6.8%; annual maintenance - 10.8%; harvesting - 23.3%; processing and packaging - 40.1% and storage and handling - 19.0%. The division of energy costs found 16.8% in establishment, 47.4% in annual maintenance 2.6% in harvesting, 11.8% in processing and 21.4% in storage and handling. Table 1-7 provides further details on these components of operation.

Costs of cuttings were developed on the assumption that they would be produced in the production/conversion facility's self-owned and operated nursery. These actual costs for cuttings will probably be lower than cutting costs for an operation which purchases cuttings from an independent profit oriented nursery.

Herbicides - Energy inputs for herbicides included production, formulation, packaging and transportation of the herbicide. Production inputs were a function of the type of herbicide and formulation, while packaging and transportation energy inputs were related to whether the herbicide was a miscible oil, powder or granules (Pimentel 1980). The type of herbicide used depended on the weed community at each individual site.

Table 1-8 lists herbicide financial and energy inputs used in establishing the plantations. The highest energy input at the Basher site was associated with Metolachlor; the only herbicide used at the Morrison site was Napropamide. The Basher site required about 6% higher herbicide energy inputs and almost 53% higher herbicide financial inputs than the Morrison site.

Table 1-7. Financial and energy costs for nursery production of hybrid poplar cuttings.

Operation	Cost per thousand cuttings			
	$/thousand	(% of total)	10^3 kcal/thousand	(% of total)
I Establishment				
Equipment	0.15		0.59	
Planting stock	0.51		2.08	
Herbicides	0.18		0.52	
Fertilizer	0.34		6.17	
Pesticides/fungicides	0.02		0.29	
Irrigation	0.51		0.98	
Rent	0.08		7.81	
Management	0.05		---	
Taxes	0.01		0.71	
	1.85	(6.8%)	19.15	(16.8%)
II Annual Maintenance				
Nursery maintenance (before establishment)	0.68		10.08	
Equipment	0.03		0.30	
Fertilizer	0.07		4.70	
Pesticides/fungicides	0.08		1.14	
Irrigation	1.66		3.94	
Rent	0.25		31.23	
Management	0.16		---	
Taxes	0.02		2.84	
	2.95	(10.8%)	54.23	(47.4%)
III Harvest				
Labor	4.44		---	
Equipment	1.96		2.93	
	6.40	(23.3%)	2.93	(2.6%)
IV Processing and Packaging				
Labor	8.00		---	
Equipment	1.67		8.30	
Building	0.98		3.24	
Packaging	0.35		1.98	
	11.00	(40.1%)	13.52	(11.8%)
V Storage and Handling				
Labor	0.29		---	
Buildings	4.83		26.09	
Energy	0.09		0.43	
	5.21	(19.0%)	26.52	(21.4%)
Total	27.43	(100.0%)	114.37	(100.0%)

Table 1-8. Herbicide energy and cost inputs used in establishing plantations.

Herbicide	Energy Inputs kcal/kg of Active Ingredient[1/]	kg of Active Ingredient/ha		Herbicide Energy Inputs kcal/ha	Herbicide Cost Inputs[2/] Cost ($)/ha
			Basher		
Glyphosate	99910	2.24		223798	92.60
Dicamba	99910	0.56		55950	23.15
Metolachlor	99910	3.36		335698	15.42
Oxyfluorfen	99910	1.12		111899	74.08
			TOTAL	727345	205.25
			Morrison		
Napropamide	86600	8.96		775936	434.56
			TOTAL	775936	434.56

[1/] Includes energy inputs for production, formulation, packaging and transport for various herbicides (Pimentel 1980).

[2/] Herbicide costs are $41.34/kg of active ingredient (a.i.) for Glyphosate, $41.34/kg a.i. for Dicamba, $4.59/kg a.i. for Metolachlor, $66.14/kg a.i. for Oxyfluorfen and $48.50/kg a.i. for Napropamide.

Fertilization - Table 1-9 lists fertilizer and lime energy inputs used in establishing the plantations. The highest energy input at both sites was associated with ammonium nitrate followed by lime, potash and phosphate. The Morrison site required about 13% higher fertilizer energy inputs than the Basher site.

Irrigation - The financial and energy analyses of the irrigation system for the project was different for the two plantation sites. The Basher site utilized a nearby stream as its water source whereas the Morrison site required the installation of a well, large pump and electric service lines. Both water sources were assumed to have the same flowrate, approximating the conditions of the Basher and Morrison sites. The number of hectares irrigated from a known flow rate of water was derived as (Doane's Agricultural Service, Inc. 1972):

$$ha = \frac{\ell/min \times h \times d \times 60 \times E}{R \times S}$$

ℓ/min = liters per minute flow rate (approximately 4163.5)

h = operating hours per day (21 hours per day)

d = operating season in days (42 d)

60 = 60 minutes per hour

E = irrigation efficiency (75% - Basher site, 85% - Morrison site)

R = 99985.89 ℓ/ha cm of coverage

S = total cm of seasonal water coverage (15.24 cm per irrigation season)

The trickle irrigation system could irrigate 122.91 ha for the Morrison site and 108.45 ha for the Basher site. Material requirements and costs were taken from Reed et al. (1976) and Funk et al. (1980) and project experience. The expected lifetime for instruments and materials were based on Pimentel (1980) and project experience.

The accounting procedure itemized all materials, costs and services for each site. Material costs were grouped as either major or minor items. Major items, representing major capital costs, included motors and pumps, screens, filters, pressure regulators, main pipes, fittings and clamps. Installation of electrical service was included as a major cost. Also, for the Morrison site, well installation was a major cost. Minor items were typically short-lived assets also identified as annual maintenance costs.

The financial analysis separated costs into annual depreciation and annual operation and maintenance. Depreciation represents the return of principal and interest charges on major items. The annual costs of operations and maintenance include labor, energy and replacement of minor items. For the Basher site total annual costs were $494.87/ha and for the Morrison site $580.78/ha (Tables 1-10 and 1-11).

Table 1-9. Fertilizer energy and cost inputs used in establishing the plantations.

Fertilizer	Energy Inputs kcal/kg of Amendment[1]	Average kg/ha		kcal/ha		Cost ($/ha)[2/]	
		Basher	Morrison	Basher	Morrison	Basher	Morrison
Ammonium Nitrate	14,700	174	174	2557800	2557800	38.35	8.35
Phosphate (P_2O_5)	2,300	147	157	338100	361100	31.00	33.11
Potash (K_2O)	2,300	184	185	423200	425500	32.14	32.32
Lime	316	3718	5441	1174888	1719356	49.15	71.93
			TOTAL	4493988	5063756	150.64	175.71

[1/] Energy inputs include energy for mining, production, transportation, storage and transfer of the fertilizer.

[2/] Fertilizer costs are $220.40/tonne for ammonium nitrate, $210.88/tonne for phosphate (P_2O_5), $174.68/tonne for potash (K_2O) and $13.22/tonne for high calcium lime.

Table 1-10. Annual financial and energy costs for LP model of Basher site commercial trickle irrigation system.

Item	Annual Cost Per Hectare			
	Cost ($)/ha	% of Total	10^3 kcal/ha	% of Total
Establishment				
Initial Electrical Installation	3.41	.69	6.009	.46
Major Materials[1/]	5.25	1.06	18.126	1.38
Labor (Major Materials)[2/]	.09	.02	---	--
Maintenance				
Minor Materials[3/]	297.48	60.11	1288.509	98.12
Labor (Minor Materials)	26.10	5.27	---	--
Operation				
Electricity	12.26	2.48	.564	.04
Labor	150.28	30.37	---	--
Total	494.87	100.00	1313.208	100.00

[1/] Major materials include main distribution costs such as motor and pump, screen, filter, pressure regulator, main pipe, fittings, and clamps.

[2/] Excludes labor for major materials that is included in the installation costs.

[3/] Minor materials include trickle irrigation components such as biwall hose, pipe, pressure regualtor, valves, gauges, and fittings.

Table 1-11. Annual financial and energy costs for LP model of Morrison site commercial trickle irrigation system.

Item	Annual Costs per Hectare			
	Cost ($)/ha	% of Total	10^3 kcal/ha	% of Total
Establishment				
Initial Electrical Installation	4.93	.85	21.849	1.58
Major Materials[1/]	71.83	12.36	37.734	2.74
Labor (Major Materials)[2/]	.05	.01	--	--
Maintenance				
Minor Materials[3/]	316.87	54.56	1306.026	94.71
Labor (Minor Materials)	21.22	3.65	--	--
Operation				
Electricity	18.05	3.11	13.393	.97
Labor	147.83	25.45	--	--
Total	580.78	100.00	1379.002	100.00

[1/] Major materials include main distribution costs such as motor and pump, screen, filter, pressure regulator, main pipe, fittings, clamps, well, steel casings, and all excavation costs.

[2/] Excludes labor for major materials that is included in the installation costs.

[3/] Minor materials include trickle irrigation components such as biwall hose, pipe, pressure regulator, valves, gauges, and fittings.

In the energy analysis inputs were separated as: major items, minor items, and energy requirements. The energy values for most materials and equipment were obtained from Pimentel (1980) and were combined with the materials used in this project. For the Basher site the annual energy cost was 1,379,002.20 kcal/ha and for the Morrison site 1,313, 108 kcal/ha (Tables 1-10 and 1-11).

The estimated irrigation financial and energy costs needed to maintain a commercial Populus hybrid plantation are given in Tables 1-10 and 1-11. These costs are based on analyses of material requirements and costs given in Reed et al. (1976), Funk et al. (1980), and Pimentel (1980). Based on these analyses, the annual financial and energy costs for establishing the irrigation system were lower than the annual maintenance and operation financial and energy costs.

Establishment Summary

Plantations of Populus hybrid NE-388 at a density of one tree/0.48 m^2 were established in 1980 and 1981. The plantations of 1.2 ha were established on two sites, and at each site three replications (0.2 ha) under four management strategies were planted in each year. The intent of replicating the management strategies of control, fertilization, irrigation and fertilization/irrigation in time was to account for growing season variation. However, the 1980 and 1981 replications were established by two completely different weed control programs.

The sites were plowed and disked prior to the 1980 planting, yet by mid July the trees were overwelmed by the herbaceous communities. Partial control of the weeds was accomplished by August but tree growth was suppressed (Figure 5). The research team was able to execute the designed weed control program for the 1981 plantings. The 1981 establishment program included applications of total kill herbicides in August (prior to planting year), plowing and/or disking in October (prior to planting year) and applications of pre-emergence herbicides at time of planting. The differential tree growth between the two growing seasons and among treatments within planting year was reflected in consistent site-treatment-year significant interaction terms in the analysis of variance testings.

In the 1980 plantings, survival ranged from 80 to 88% over site and treatments with a mean of 83%. In the 1981 plantings, survival ranged from 84 to 97% over site and treatments with a mean of 90%. None of the four management strategies and neither site consistently influenced tree survival. The 1980-1981 differences in the likelihood of a tree surviving at the end of the first growing season should not be only ascribed to weed control programs. Quality of planting stock, time of planting, planting crew skill and damage from mechanical weed control (1980) were the major reasons for the 83% survival in 1980 and 90% survival in 1981.

The overall survival of 86% may reflect a highly successful production size establishment effort. Annual planting of 50 to 200 ha should be considered successful if 75% of the trees survive and are free to grow at the end of the first growing season.

With a good weed control program (1981), neither the management strategies nor the sites produced a substantial advantage in total height or stem diameter growth during or at the end of the first growing season. Tree size was improved, over other treatments, with combined fertilization and irrigation at the Basher site but the advantage was not sustained at the Morrison site. In contrast, there were tree size advantages to fertilizing for the plantings that did not have an effective weed control program (1980). There were no differences between sites for the 1980 plantings and neither site was irrigated in 1980.

A summary of the financial and energy costs for establishing a commercial plantation (Table 1-12) lists the highest operational cost as planting (including nursery) followed by herbicides, disc, harrow and mower. However, the energy costs for fertilization were higher than irrigation while financial costs for irrigation were higher than fertilization. In addition, the costs for cultural amendments were higher at the Morrison site. These data were used as inputs to the LP model.

Table 1-12. Summary of the financial and energy establishment costs for the first rotation.

	Basher Site		Morrison Site	
Establishment	10^6 kcal/ha	$/ha[1/]	10^6 kcal/ha	$/ha[1/]
Operation				
Mower	.012	2.65	.012	2.65
Disc	.031	4.77	.031	4.77
Herbicide	.154	59.84	.154	59.84
Harrow	.014	3.36	.014	3.36
Plant	.541	190.48	.541	190.48
	.752[2/]	261.10[3/]	.752[2/]	261.10[3/]
Cultural Amendment				
Fertilization	12.327	410.24	15.428	551.09
Irrigation	5.253	1754.67	5.516	2059.34
	17.580	2164.91	20.944	2610.43

[1/] Total cost for 4 year period, discounted at 5% annual.

[2/] The total establishment cost of 3.76 x 10^6 kcal/ha was divided over 5 rotations, with the cost for any one rotation placed at .752 x 10^6 kcal/ha.

[3/] The total establishment cost of $917.64/ha was prorated over 5 rotations (20 years), with the cost for the first rotation ($261.10/ha) representing the discounted sum of the first 4 years of annuity payments.

Task 2 - Plantation Biomass Production

Task 2 was designed to determine the production yields, growth rates and properties of the biomass as a fuel or chemical feedstock. In addition, financial and energy inputs needed to operate and maintain the plantations under the selected management strategies were determined.

Plantation Maintenance - Second Year, Third Year and Fourth Year

The four management strategies (control, fertilization, irrigation and fertilization/irrigation) were continued into the second, third and fourth growing seasons. All of the 1980 treatment units received herbicide treatments at the beginning of the second growing season similar to those described for establishment of the 1981 plantings. Normally, weed control in SRIC plantations with close spacings is completed during the first growing season. However, because of the poor weed control in 1980, weed control procedures were used in the second year to insure that the measured responses were independent of weed competition. Weed control was continued on selected 1980 planted treatment units until the trees dominated the site. None of the 1981 planted units received weed control treatment after establishment.

Soil samples for the fertilization treatment units were obtained in the fall of each year. These samples were collected to assess fertility status and develop fertilizer and/or lime recommendations based on site specific recommendations to produce 47 t/ha of corn silage. Each plot was independently evaluated and the amount of fertilizer and/or lime needed to maintain a non-limiting soil fertility level was applied in the spring of each year. The average analyses of the Ap and upper 15 cm of the B horizons soil samples collected before the second year by year of planting, site and treatment are presented in Appendix B (Tables B-1, 2). Individual plot soil test results were used to develop the maintenance fertilization program presented in Appendix B (Tables B-3, 4, 5). A summary of the fertilizer and lime amounts applied at the beginning of each growing season, and accumulated fertilizer amounts, by plantation site and treatment are presented in Tables 2-1, 2-2 and 2-3.

Irrigation was cancelled in 1980 but was applied in the second, third and fourth growing seasons (1981-1983) to the three replications planted in 1980. The trees planted in 1981 were irrigated in the first through fourth growing seasons (1981-1984). A summary of the weather conditions and the amount of water added to the irrigation treatment units is presented in Table 1-4 for 1981, 2-4 for 1982, 2-5 for 1983 and 2-6 for 1984.

The fertilization/irrigation treatment strategy combined the procedures for the two management strategies. The amounts of fertilizer and/or lime added at the beginning of each growing season were determined in the same manner as for the fertilization units and are summarized in Tables 2-1, 2-2 and 2-3. Weather conditions and annual amounts of irrigation water for the 1980 and 1981 planted treatment units are summarized in Tables 1-4 and 2-4, 2-5 and 2-6.

Table 2-1. Summary[1/] of the amount of fertilizer and lime applied at the start of the second growing season, and accumulated one and two year amendments, by plantation site and treatment.

Plantation Site and Treatment	N	P_2O_5	K_2O	Lime	Mg
	- - - - - - - - -		kg/ha	- - - - - - - - - -	
Beginning of 2nd Growing Season					
Basher					
Fertilization	168	117	163	1495	91
Fertilization/ Irrigation	168	72	148	1028	64
Morrison					
Fertilization	168	73	121	4203	143
Fertilization/ Irrigation	168	83	109	3363	122
Accumulative for 1 and 2 Growing Seasons					
Basher					
Fertilization	347	232	305	5213	134
Fertilization/ Irrigation	347	219	332	4746	107
Morrison					
Fertilization	347	229	315	9644	291
Fertilization/ Irrigation	347	239	294	8804	270

[1/] Amounts added by year of planting and individual replication for each site and treatment are given in Appendix B (Table B-3).

Table 2-2. Summary[1/] of the amount of fertilizer and lime applied at the start of the third growing season, and accumulated one, two and three year amendments, by plantation site and treatment.

Plantation Site and Treatment	N	P_2O_5	K_2O	Lime	Mg
	- - - - - - - - -		kg/ha	- - - - - - - - -	
Beginning of 3rd Growing Season					
Basher					
Fertilization	168	89	121	2802	88
Fertilization/ Irrigation	168	72	115	747	28
Morrison					
Fertilization	168	103	72	3176	122
Fertilization/ Irrigation	168	76	82	2802	108
Accumulative for 1, 2 and 3 Growing Seasons					
Basher					
Fertilization	510	321	427	8015	217
Fertilization/ Irrigation	510	290	446	5493	135
Morrison					
Fertilization	510	332	387	17443	413
Fertilization/ Irrigation	510	315	393	11606	378

[1/] Amounts added by year of planting and individual replication for each site and treatment are given in Appendix B (Table B-4).

Table 2-3. Summary[1/] of the amount of fertilizer and lime applied at the start of the fourth growing season, and accumulated one, two, three and four year amendments, by plantation site and treatment.

Plantation Site and Treatment	N	P_2O_5	K_2O	Lime	Mg
	kg/ha				
Beginning of 4th Growing Season					
Basher					
Fertilization	168	54	20	1308	41
Fertilization/ Irrigation	168	72	85	1495	32
Morrison					
Fertilization	168	45	33	1681	105
Fertilization/ Irrigation	168	62	27	2055	75
Accumulative for 1, 2, 3 and 4 Growing Seasons					
Basher					
Fertilization	678	374	446	9322	248
Fertilization/ Irrigation	678	362	531	6987	166
Morrison					
Fertilization	678	377	426	14506	512
Fertilization/ Irrigation	678	377	424	13661	453

[1/] Amounts added by year of planting and individual replication for each site and treatment are given in Appendix B (Table B-5).

Table 2-4. Monthly summary of weekly maximum and minimum temperatures, rainfall and irrigation for the Basher and Morrison plantation sites in 1982.

Site-Measurement	June	July	August
Basher			
Temperature[1/] (C°)			
Weekly Minimum	11.4	15.3	12.0
Weekly Maximum	24.9	28.9	25.8
Rainfall[1/] (cm)	10.0	10.6	3.2
Irrigation[2/] (cm)	0.0	0.0	6.1
Morrison			
Temperature[1/] (C°)			
Weekly Minimum	11.9	14.5	12.1
Weekly Maximum	23.2	28.2	25.1
Rainfall[1/] (cm)	11.8	10.3	5.6
Irrigation[2/] (cm)	4.8	0.0	7.6

[1/] Average weekly values are presented in Appendix B (Table B-6).

[2/] Amount of water added to individual plots, by treatment, site and date, are presented in Appendix B (Tables B-7, 8).

Table 2-5. Monthly summary of weekly maximum and minimum temperatures, rainfall and irrigation for the Basher and Morrison plantation sites in 1983.

Site-Measurement	June	July	August
Basher			
Temperature[1/] (C°)			
Weekly Minimum	12.7	13.5	13.1
Weekly Maximum	28.5	29.6	29.2
Rainfall[1/] (cm)	6.9	3.0	1.8
Irrigation[2/] (cm)	0.0	0.8	7.7
Morrison			
Temperature[1/] (C°)			
Weekly Minimum	12.9	13.9	14.6
Weekly Maximum	27.5	28.7	28.6
Rainfall[1/] (cm)	7.2	3.3	1.9
Irrigation[2/] (cm)	0.0	6.8	7.8

[1/] Average weekly values are presented in Appendix B (Table B-9).

[2/] Amount of water added to individual plots, by treatment, site and date, are presented in Appendix B (Tables B-10, 11).

Table 2-6. Monthly summary of weekly maximum and minimum temperatures, rainfall and irrigation for the Basher and Morrison plantation sites in 1984.

Site-Measurement	June	July	August
Basher			
Temperature[1/] (C°)			
Weekly Minimum	14.2	14.4	15.4
Weekly Maximum	27.0	25.6	27.4
Rainfall[1/] (cm)	13.3	7.8	16.8
Irrigation[2/] (cm)	1.6	2.6	0.8
Morrison			
Temperature[1/] (C°)			
Weekly Minimum	13.6	13.8	14.8
Weekly Maximum	26.5	25.6	26.2
Rainfall[1/] (cm)	12.1	7.7	13.5
Irrigation[2/] (cm)	3.6	4.1	1.1

[1/] Average weekly values are presented in Appendix B (Table B-12).

[2/] Amount of water added to individual plots, by treatment, site and date, are presented in Appendix B (Tables B-13, 14).

Management Strategies - Fertilization

Second Year - The fertilized trees planted in 1980 at the beginning of the second growing season (June 19) grew in height significantly faster than the control or irrigated trees and maintained the greater growth throughout 1981 (Appendix B, Table B-15 and Figure 6). By the end of the growing season, the two year old fertilized trees grew an average of 2.48 m in height compared to 1.08 m for the control trees and 1.53 m for the irrigated trees. There were some significant Basher-Morrison site differences in the fertilized two year old elongation values but the values during the growing season, measured at the end of the year, were not significantly different (Appendix B, Table B-15).

Average survival of all 1980 planted two year old continuous inventory fertilized trees (80%) was lower than the control tree survival, 89% (Table 1-2). Total height of the two year old fertilized trees averaged 3.5 m on the Basher site and 3.4 m on the Morrison site. These values were substantially greater than the Basher and Morrison control tree averages of 1.9 and 1.6 m, respectively (Table 1-3). Average diameter at 15 cm above ground was also greater for the surviving two year old fertilized trees (Basher 2.5 and Morrison 2.4 cm) compared to the two year old control trees (Basher 1.5 and Morrison 1.4 cm).

In contrast, the fertilized trees planted in 1981 did not have second year height growth greater than the control trees (Appendix B, Table B-16 and Figure 6). These second year elongation values were calculated from a similar data collection base as the 1980 planted trees.

Average survival of the 1981 planted two year old control and fertilized trees was 91%. Total height for the two year old fertilized trees planted at the Basher site averaged 4.5 m and the trees planted at the Morrison site averaged 4.7 m. These values were not significantly different from each other or the control trees planted at the Morrison site which averaged 4.6 m, but they were significantly greater than the 4.2 m average for Basher control trees (Table 1-3). There was no significant difference between the fertilized Basher and Morrison stem diameters (3.0 and 3.1 cm, respectively). The fertilized tree diameters, by site, were significantly greater than the control tree average of 2.7 cm for the Basher site, but not for the Morrison site control value of 3.0 cm.

Second Year Fertilization Summary - The one year old 1980 planted fertilized trees were slightly larger in total height and stem diameter than the control trees. In the second growing season, the rapid height growth of the fertilized trees, particularly at the beginning of the year, suggests that the root system for the fertilized trees was more developed in the establishment phase than the non-fertilized trees. In the second growing season of the 1981 planted trees both the control and fertilized trees grew rapidly throughout the year and there was no difference between the two treatments. Apparently the inherent soil nutrient status at these two plantation sites was sufficient to support maximum tree height growth - if the weeds were controlled in the establishment year. If weeds were not controlled in the establishment year (1980 plantings), fertilization resulted in greater second season total height growth than non-fertilized trees. The contrasting second year elongation pattern between the 1980 and 1981 planted trees is presented in Figure 6.

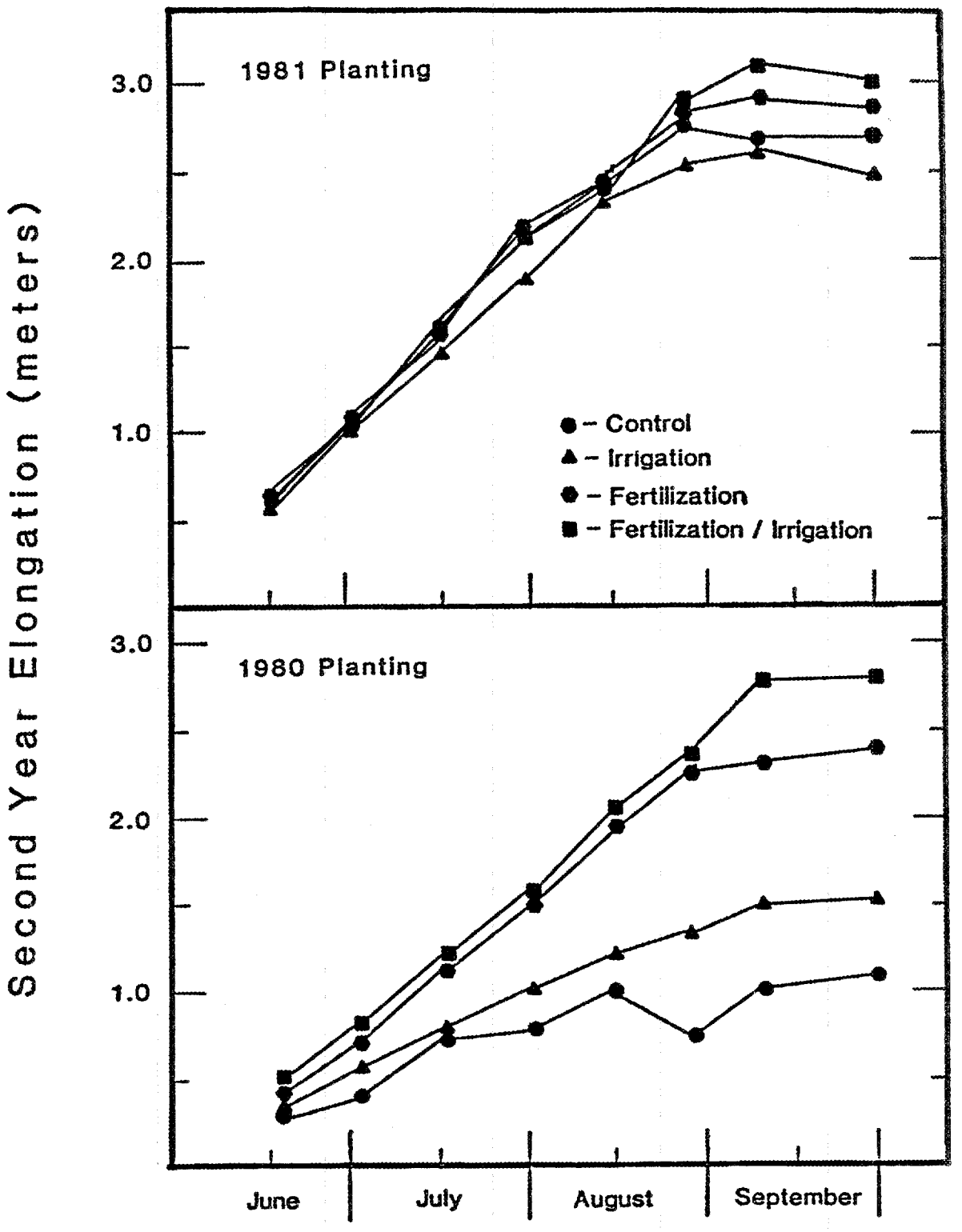

Figure 6. Elongation in the second growing season for trees planted in 1980 and 1981 by treatment. Treatment values are averaged over site and each point is an average of 60 randomly and independently selected trees.

The combined one and two year growth advantage of fertilizing trees established with poor (1980 plantings) weed control resulted in two year old trees that were taller and larger in diameter than non-fertilized trees (Figures 7 and 8, respectively). When fertilizer was applied to trees with good weed control in the establishment year (1981 plantings), there was apparently no growth advantage in either the first or second growing seasons. However, by the end of the second growing season the fertilized trees were beginning to accumulate a size advantage over the non-fertilized trees (Figures 7 and 8).

Third Year - Average survival of all 1980 planted three year old control trees (87%) was greater than the average survival of the fertilized trees (79%). Total height of the fertilized trees averaged 5.7 m at the Basher site and 5.8 m at the Morrison site. There was no significant site difference in the total height of the three year old fertilized trees (Table 1-3). The fertilized trees were significantly taller than the control trees at both the Basher site (average of 4.1 m) and the Morrison site (average of 3.9 m). The average three year old total height for the Basher control trees was significantly greater than the Morrison control value (Table 1-3). Diameter at 15 cm above ground followed a pattern similar to total height in the significant separation between sites for the fertilized and control trees. Stem diameter averaged 3.7 cm for the fertilized Basher trees and 3.6 cm for the Morrison fertilized trees. The three year old stem diameter averaged 2.7 and 2.4 cm for the Basher and Morrison control trees, respectively.

Averaged over both plantation sites, the three year old survival for the control and fertilized 1981 planted trees was 90% (Table 1-2). Average total height for the three year old fertilized trees planted at the Basher site (5.7 m) was not significantly lower than the fertilized trees planted at the Morrison site (5.9 m) and there was no site difference in average stem diameter for this treatment (Table 1-3). Stem diameter for the three year old 1981 planted fertilized trees at the Basher site averaged 4.0 cm and 3.9 cm for the trees growing at the Morrison site. Fertilization resulted in three year old trees that were significantly taller and larger in diameter than the control treatment at the Basher site but the differences were not significant at the Morrison site (Table 1-3).

Third Year Fertilization Summary - Accumulated total height and diameter for ages one, two and three years of the 1980 planted trees are presented in Figures 7 and 8. These figures indicate that with poor weed control in the establishment year there was a substantial depression in control treatment tree growth in the first and second growing seasons, as compared to the fertilized trees. However, in the third growing season of the 1980 planted trees there were no differences in average total height increment (about 2.3 m) between the trees growing at either site and between the fertilized and control treatment units (Figure 7). There was a similar standard diameter increment in the third growing season for the control and fertilized trees at both sites (Figure 8). Second and third year total height and diameter increments were similar for the 1980 planted fertilized trees. Of the 1981 planted fertilized trees, the second year's total height increment was greater than that of the third year. The second year 1981 planted fertilized diameter increment was also greater than that of the third year, but not by as much as total height. Averaging over sites,

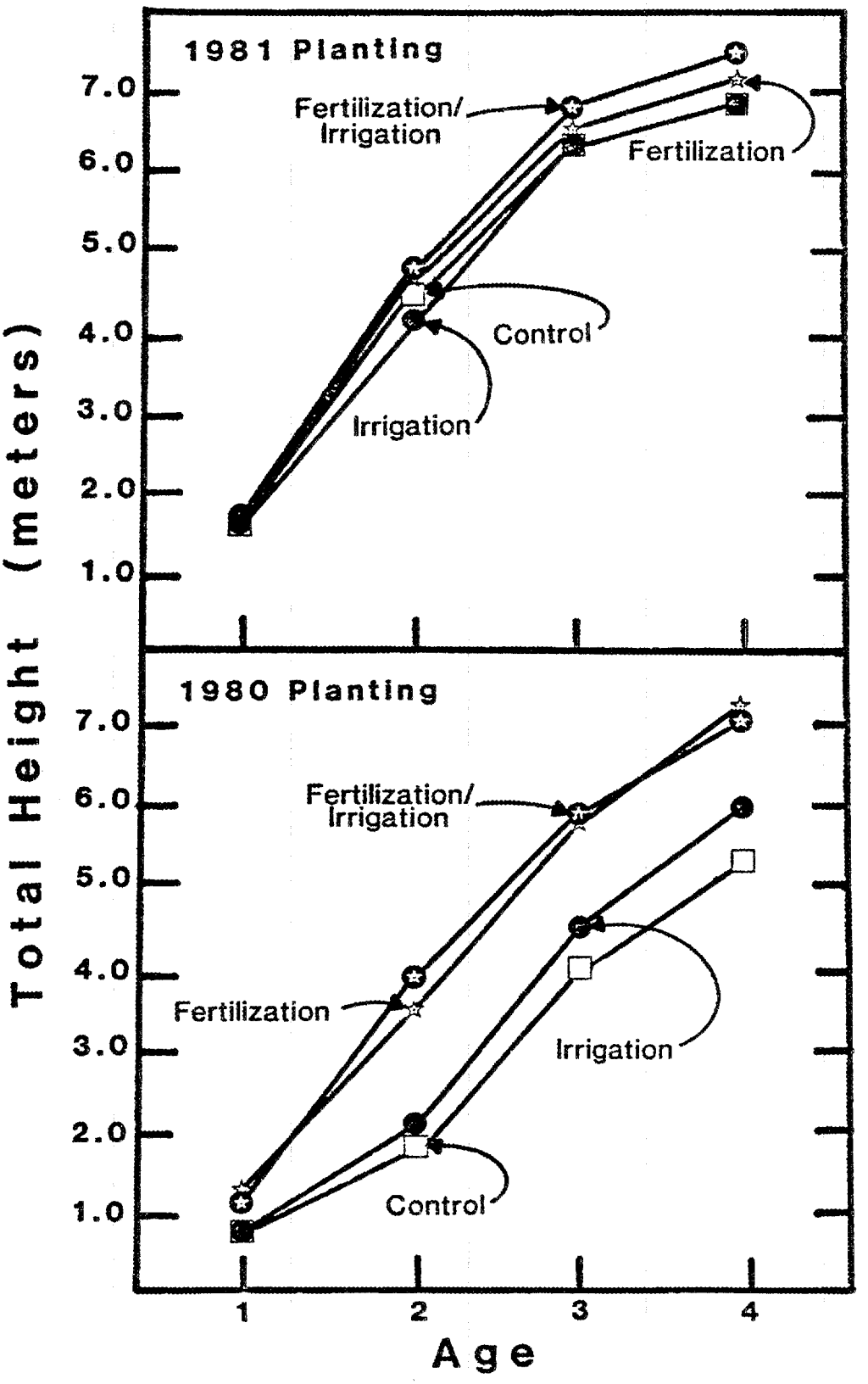

Figure 7. Average total height for the 1980 and 1981 planted replications, by age. Treatment values are averaged over site.

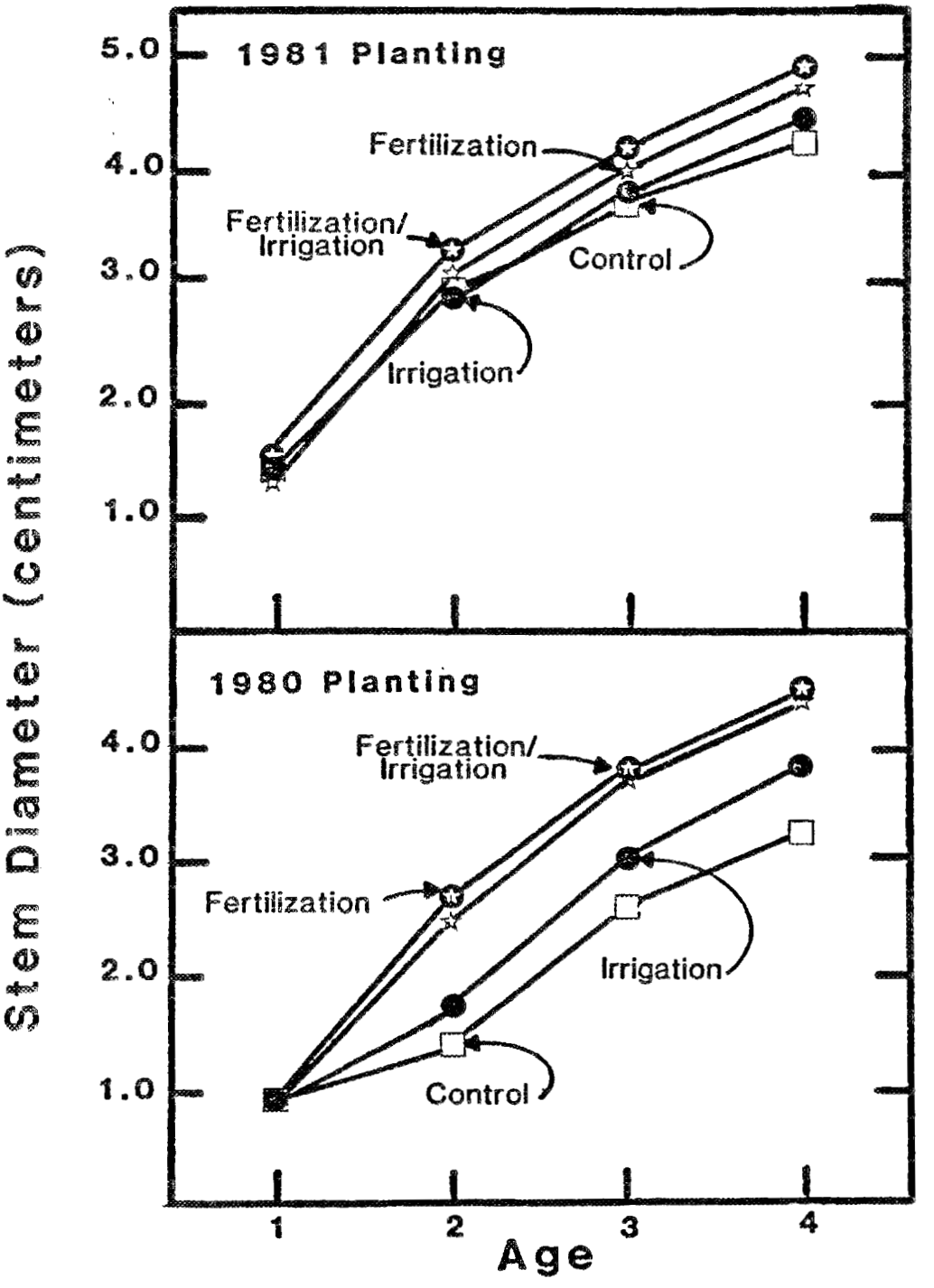

Figure 8. Average stem diameter at 15 cm above ground for the 1980 and 1981 planted replications, by age. Treatment values are average over site.

the third year fertilized height increments were 2.3 m and 1.1 m for 1980 and 1981 planted trees, respectively.

Weed control and year of establishment had no important net effect on three year old fertilized average total height values (Table 1-3). In contrast, averaging over sites, the 1980 planted fertilized trees were about 0.30 cm smaller in diameter than the 1981 planted fertilized trees.

Averaged over both sites, total three year old control heights were 4.0 m and 5.7 m for the 1980 and 1981 planted trees, respectively. Average three year old stem diameter of the 1980 planted control trees was about 1.1 cm less than the 1981 planted control tree value.

Weed control had no effect on the average three year old total height values and a slight effect on the diameter values, if the trees were fertilized. However, weed control methods did have a major effect on the control tree average size values. These weed control differential growth patterns had a major effect on the control-fertilization tree size comparisons.

Fourth Year - Average survival of all 1980 planted four year old control trees (86%) was greater than the average survival of the fertilized trees (74%). Total height of the fertilized trees averaged 7.4 m at the Basher site and 6.9 m at the Morrison site. This height difference was significant (Table 1-3). The fertilized trees were significantly taller than the control trees at both the Basher site (average of 5.4 m) and the Morrison site (average of 5.2 m). Diameter at 15 cm above ground followed a pattern similar to total height in the significant separation between sites for the fertilized and control trees, except the Basher control trees were significantly larger in diameter than the Morrison control trees. Stem diameter of the fertilized Basher trees averaged 4.6 cm and 4.2 cm for the Morrison fertilized trees. The four year old control tree stem diameters averaged 3.5 cm and 3.3 cm for the Basher and Morrison sites, respectively.

Averaged over both the Basher and Morrison plantation sites, the four year old survival of the control and fertilized 1981 planted trees was 86% (Table 1-2). Total height of the four year old fertilized trees averaged 7.1 m at both the Basher and Morrison sites. These values were significantly greater than the control treatment average total height values of 6.8 m and 6.7 m for the Basher and Morrison sites, respectively (Table 1-3). Average stem diameter of the 1981 planted fertilized trees at the Basher site (4.8 cm) was significantly greater than the average value for the fertilized trees at the Morrison site (4.6 cm). For both sites the fertilized tree average stem diameter was greater than the control tree average (4.2 cm for each site, Table 1-3).

Fourth Year Fertilization Summary - Accumulated total height and diameter for ages one through four years of the 1980 planted trees displayed in Figures 7 and 8 indicate a substantial depression in control treatment tree growth in the first and second growing seasons, as compared to the fertilized trees. However, in the third and fourth growing seasons there was little difference in average total height increment between the trees growing at either site and between the fertilized and control treatment

units (Figure 7). There was a similar standard diameter increment in the third and fourth growing seasons for the control and fertilized trees at both sites (Figure 8). Apparently the 1980 planted control trees have recovered from the establishment year weed competition but they remained smaller than the fertilized trees. At the end of the first rotation, fertilization at both sites increased average total height and stem diameter values by about 30% over the control treatment.

In the first three years, the fertilized average height and diameter growth rates for the 1981 planted trees were similar to the control growth rates (Figure 7 and 8). In the fourth growing season and averaged over both the Basher and Morrison sites, the fertilized trees grew 30% more than the control trees in height and about 45% more than the control trees in diameter.

The 1980 planted fertilized trees (poor weed control) had slow height growth in the first year and rapid growth in the second, third and fourth growing seasons. The 1981 planted fertilized trees (good weed control) had rapid height growth in the first two years with slower growth in the third and fourth growing seasons. Total height of four year old fertilized trees was about 7.0 m at both sites for both planting years. Therefore, while weed control did affect the annual rate of height growth of fertilized trees, it did not apparently influence four year total height. Stem diameter of four year old fertilized trees averaged 4.4 cm and 4.7 cm for 1980 and 1981 planted trees, respectively.

Total height of four year old control trees averaged 5.3 m and 6.8 m for 1980 and 1981 planted trees, respectively. Diameter of four year old control trees averaged 3.4 cm and 4.2 cm for 1980 and 1981 planted trees, respectively. The depression in control tree growth caused by poor weed control (1980 planted trees) resulted in a substantial difference in height and diameter between control and fertilized 1980 planted trees. With good weed control, only a slight difference between control and fertilized 1981 planted trees was observed.

Management Strategies - Irrigation

Second Year - The second growing season elongation measurements for the 1980 planted trees and statistical differences among treatments are presented in Appendix B (Tables B-15, 16). Irrigation at the Basher site started on July 18 and was interrupted by 6.30 cm of rain on July 20-21 (Appendix A, Table A-11). Irrigation was resumed on Aug 5-7 and continued through August until the rains of August 31 to September 6 terminated the program for the year. An average of 77 ℓ/m^2 of water was added to the two year old trees growing at the Basher site (Appendix A, Table A-11). Irrigation at the Morrison site started on August 5 and continued until August 28. An average of 91 ℓ/m^2 of water was added to the two year old trees growing at the Morrison site (Appendix A, Table A-12).

The irrigation program at the Basher site for the 1980 planted trees resulted in a sustained significant increase in second growing season elongation after July 29, as compared to the control elongation (Appendix B, Table B-15). The Basher irrigated trees grew 31% more in height than the Basher control trees but significantly less than fertilization or

fertilization/irrigation trees. The Morrison site irrigation program in 1981 was of shorter duration than the Basher program and resulted in increased growth over the controls after August 28 (Appendix B, Table B-15). From late August to the end of the growing season the irrigation trees at the Morrison site had significantly greater elongation than the control trees. The September 29 measurements indicated that the water amended trees grew 60% more in height than the control trees but substantially less than the fertilization or fertilization/irrigation trees.

In 1982, the trees planted in 1981 started their second growing season. Rainfall in April and early May 1982 was low and the Morrison soil became water deficient by mid-May. Irrigation was started at the Morrison site on May 10 and continued for 17 cycles until September 3 (Appendix B, Table B-8). An average of 203 ℓ/m^2 was applied to the Morrison two year old irrigated trees that were planted in 1981. This amount of water added was considerably greater than the average of 79 ℓ/m^2 which was added to the two year old irrigated 1980 planted trees during the 1981 growing season.

The soil at the Basher site did not become water deficient until August 1982. Irrigation of the two year old 1981 planted trees growing at the Basher site was started August 16 and continued until September 3 for a total of six cycles (Appendix B, Table B-7). The average amount of water added was 55 ℓ/m^2. Irrigation to the two year old 1980 planted treatment units was initiated earlier (August 5, 1981) and the amount added was slightly greater (57 ℓ/m^2) than the irrigation program for the two year old 1981 planted treatment units.

The pattern of second growing season elongation for the 1981 planted trees is presented in Figure 6. These results contrast the second growing season elongation advantage associated with irrigating the 1980 planted trees (Figure 6). Apparently, when the trees were established in a relatively weed free environment (1981 plantings) the root systems were more developed and were capable of supplying sufficient amounts of water for tree growth. When establishment year weed control was not effective (1980 plantings), irrigation increased height growth in the second growing season. Since the 1980 plantings were not irrigated during the establishment phase, the relative first year growth advantage - with weed competition - could not be evaluated.

Second Year Irrigation Summary - Average two year old survival of the 1980 and 1981 planted continuous inventory trees was about the same for the control and irrigation treatments (Table 1-3). Average total height of the irrigated two year old 1980 planted trees was significantly greater than the control tree average total height at the Basher site but not at the Morrison site (Table 1-3). At both the Basher and Morrison sites, the irrigation two year old total height for the 1980 planted trees was less than the fertilization and fertilization/irrigation treatment values. Irrigation of the two year old 1981 planted trees produced different results. At the Morrison site, there were no differences in average total height values for control (4.6 m), irrigation (4.6 m) or fertilization (4.7 m) or fertilization/irrigation (4.7 m) treatments (Table 1-3). At the Basher site, the two year old average total height of the irrigated 1981 planted trees (3.7 m) was significantly less than the control (4.2 m),

fertilization (4.5 m) and fertilization/irrigation (4.7 m) treatment units (Table 1-3). The reason for the reduced average tree height of the Basher irrigated trees was influenced by one replication where the irrigated trees were very small, compared to the trees in the surrounding replications. This plot was located in a depression and poor internal soil drainage may have restricted tree height growth.

Relative average diameter at 15 cm above ground for the two year old irrigated trees, as compared to the other treatments by year of planting, was similar to relative total tree height differences. At the Basher site, the 1980 planted irrigation treatment units had an average diameter (2.0 cm) that was significantly larger than the control treatment units (1.5 cm) but significantly less than the fertilization (2.5 cm) and fertilization/irrigation (2.7 cm) treatment units. Average two year old diameter for the 1980 planted irrigation treatment units at the Morrison site (1.4 cm) was the same as for the control treatment unit (1.4 cm) and significantly lower than the fertilization (2.4 cm) and fertilization/irrigation (2.7 cm) treatment units. Average two year old diameter of the irrigated 1981 planted trees growing at the Basher and Morrison sites (2.5 cm and 3.1 cm, respectively) were (a) significantly less than all other Basher treatments (control, fertilization and fertilization/irrigation values of 2.7, 3.0 and 3.2 cm, respectively); and (b) significantly greater than the Morrison control (3.0 cm), the same as for fertilization (3.1 cm) but significantly lower than fertilization/irrigation (3.3 cm) treatment values.

Third Year - In 1982 (third growing season for the 1980 planted trees), the April and early May rainfall was low and the Morrison soil became water deficient by mid-May. Irrigation was started at the Morrison site on May 10 and continued for 17 cycles until September 3 (Appendix B, Table B-8). An average of 207 ℓ/m^2 of water was applied to the three year old 1980 planted trees growing at this site. The soil at the Basher site was not water deficient until mid-August. Irrigation of the three year old 1980 planted trees at the Basher site was initiated August 16, continued for six cycles and discontinued on September 3 (Appendix B, Table B-7). An average of 72 ℓ/m^2 was applied to the three year old 1980 planted Basher irrigated treatment units.

Rainfall in 1983 (third growing season for the 1981 planted trees) was adequate for tree growth until July (Table 2-4). Irrigation to the three year old 1981 planted trees growing at the Morrison site was started July 11 and continued for 12 cycles until September 9 (Appendix B, Table B-11). An average of 155 ℓ/m^2 was applied to the trees growing at this site. Irrigation to the three year old 1981 planted trees growing at the Basher site was started July 25 and continued to August 30. An average of 86 ℓ/m^2 was applied in seven cycles (Appendix B, Table B-10).

Average three year old survival of the 1980 planted irrigation trees was as good as the control trees and appeared to be better than the fertilization and fertilization/irrigation values (Table 1-3). The relative growth response to irrigation, as compared to the other treatments, displayed in the second growing season of the 1980 planted trees was continued into their third growing season. Average three year old total height (4.9 m) of the irrigation 1980 planted trees was significantly greater than the control tree average height (4.1 m) for those replications growing at the

Basher site but not for those at the Morrison site. The three year old Morrison control trees averaged 3.9 m and the irrigated trees averaged 4.2 m. At both sites, the irrigation trees were significantly shorter than either the fertilization or fertilization/irrigation trees (Table 1-3). The three year old diameter of the irrigation trees followed the same pattern as total height with irrigation increasing average diameter at the Basher site but not at the Morrison site (when compared to control), and irrigation resulted in average diameters that were not as large as fertilization or fertilization/irrigation (Table 1-3).

Average three year old survival values of the 1981 planted irrigation trees were similar to all other treatments (Table 1-3). Average three year old total height of the irrigation 1981 planted trees (5.3 m) was significantly less than the control (5.6 m) and fertilization average total height (5.7 m) for the replications growing at the Basher site. There were no significant control-irrigation (5.8 vs 6.0 m, respectively) or fertilization-irrigation (5.9 vs 6.0 m, respectively) differences for the replications growing at the Morrison site (Table 1-3). The relative differences in three year old average stem diameter for the irrigation trees, as compared to the other treatments, were similar to the average total height differences (Table 1-3).

Third Year Irrigation Summary - Irrigation in the second and third growing seasons (Figures 7 and 8) resulted in small but continued growth gains over the control treatment, particularly at the Basher site. Averaged over both sites, irrigation to trees with poor weed control in the establishment year resulted in a three year old total height of 4.5 m and diameter of 3.0 cm. The control three year old average total height and diameter were 4.0 m and 2.6 cm, respectively. However, the irrigation treatment average total height and diameter values were considerably less than either the fertilization or the fertilization/irrigation values.

Irrigation to trees established with good weed control (1981 planting) had contrasting results (Figures 7 and 8). There was no apparent three year old irrigation over control advantage for the 1981 planted trees, and irrigated average tree size values were only slightly less than the fertilization or fertilization/irrigation average tree size values.

Fourth Year - The 1983 irrigation (fourth growing season for the 1980 planted trees) at the Morrison site was started July 11 and continued for 12 cycles ending on September 9 (Appendix B, Table B-11). A total of 145 ℓ/m^2 was applied to the 1980 planted four year old trees. Irrigation at the Basher site was started July 25 and ended August 30 (Appendix B, Table B-10). There was a total of 85 ℓ/m^2 applied in seven irrigation cycles for the 1980 planted trees growing at the Basher site.

The 1984 irrigation (fourth growing season for the 1981 planted trees) at the Morrison site was started June 13 and continued for seven cycles ending August 6 (Appendix B, Table B-13). A total of 84 ℓ/m^2 of water was applied to the four year old 1981 planted trees growing at the Morrison site before abundant rain in August (13.5 cm, Table 2-6) discontinued the need for irrigation. Irrigation to the four year old trees growing at the Basher site was started June 26 and continued for four cycles ending August 6. A total of 43 ℓ/m^2 was applied to the trees growing at the Basher site

before the abundant rainfall in August (16.8 cm, Table 2-6) discontinued the need for irrigation.

There was no difference in the four year old survival for the 1980 planted control trees (82%) and irrigation trees (84%) growing at the Basher site (Table 1-3). At the Morrison site, the four year old tree survival was 89% for the control treatment and 79% for the irrigation treatment (Table 1-3). Irrigation of the 1980 planted trees growing at the Basher site resulted in an average four year old total height of 6.2 m (Table 1-3). The irrigated trees were significantly taller than the control (5.4 m) but significantly less than fertilization (7.4 m) and fertilization/irrigation (6.9 m). At the Morrison site, the differences among the treatments were the same as recorded at the Basher site but the average four year old total height of the Morrison irrigation trees of 5.6 m was less than the Basher irrigation value (Table 1-3). The relative differences in the four year old stem diameter for the irrigation trees, as compared to the other treatments, were similar to the average total height differences. Average four year old stem diameter for the Basher and Morrison irrigation trees was 4.0 and 3.6 cm, respectively. For both average total height and stem diameter at both sites, the irrigation treatment four year old values were significantly lower than either the fertilization or the fertilization/irrigation treatment.

Irrigation to the 1981 planted trees resulted in similar control-irrigation four year old survival differences as the 1980 planted trees. However, four years of irrigation to the 1981 planted trees did not result in the same growth response, when compared to the control, as recorded for three years of irrigation to the 1980 planted trees. With the exception of a significantly greater average stem diameter at the Morrison site, irrigation did not increase four year old average tree size values over the control treatment. At the end of the first rotation the irrigation trees at the Basher and Morrison sites averaged 6.7 and 6.9 m in total height, and 4.1 and 4.6 cm in stem diameter, respectively (Table 1-3). These site specific values were significantly lower than fertilization at the Basher site but not at the Morrison site, and were significantly less than the fertilization/irrigation values at both sites.

Fourth Year Irrigation Summary - When compared to control and averaged over both sites, irrigation resulted in increased average total height and stem diameter growth during the second, third and fourth growing seasons (Figures 7 and 8). Irrigation in the second, third and fourth growing seasons of trees established with poor weed control resulted in about a 12% increase in the four year old tree size values over the control treatment. However, the irrigation treatment average four year old total height and diameter values were substantially less than the fertilization and fertilization/irrigation treatments.

In contrast, four years of irrigation of trees established with good weed control (1981 planting) had no apparent first rotation benefit (Figures 7 and 8). Averaged over both plantation sites, the height growth rates of the control and irrigated trees were similar, and average four year old total height of 6.8 m was the same for both treatments. Diameter growth of the irrigation trees was slightly greater than the control trees in the third and fourth growing seasons (Figure 8). Average four year old

diameter for the irrigated trees (4.4 cm) was significantly greater than the control value (4.2 cm) but this difference was relatively minor. Averaged over both sites, the 1981 planted irrigated trees had significantly lower total height and stem diameter values than either the fertilized or the fertilized/irrigated trees.

Management Strategies - Fertilization/Irrigation

Second Year - For the 1980 planted replications, the combined effect of fertilization in the first and second growing seasons, and irrigation in the second growing season resulted in two year old trees with a similar elongation rate to the fertilization trees (Figure 6 and Appendix B, Table B-15). Second growing season elongation values indicated that there were no sustained significant differences between the fertilization and fertilization/irrigation trees at the Basher site (Figure 6). At the Morrison site, the fertilization/irrigation trees had significantly greater elongation values than the fertilization trees (Appendix B, Table B-16). Since this trend started before the beginning of the irrigation program, these differences appear unrelated to the irrigation treatment effect. One explanation may be the exceptionally strong growth of one fertilization/irrigation plot.

Average two year old total height of the 1980 planted fertilization/irrigation trees growing at the Basher site was 3.7 m. This value was substantially greater than the control (average of 1.9 m) and irrigation (average of 2.6 m) trees but not significantly greater than the fertilization (average of 3.5 m) treatment units (Table 1-3). Average total height of the fertilization/irrigation trees growing at the Morrison site was 4.0 m and this value was significantly greater than all other treatments. The average two year old total height values of the Morrison control, irrigation and fertilization trees were 1.6, 1.5 and 3.4 m, respectively.

Average two year old stem diameter of the 1980 planted fertilization/irrigation treatment units was significantly greater than all other treatments at both sites (Table 1-3). Combined for both sites, the average diameter of the fertilization/irrigation trees was 2.7 cm and the control, irrigation and fertilization values were 1.4. 1.7 and 2.5 cm, respectively.

Relative to the other treatments, the fertilization/irrigation height growth in the second growing season of the 1981 planted trees was different than for the 1980 planted trees (Figure 6). The 1981 planted trees were fertilized and irrigated in both the first and second growing seasons, and weed control was more effective for the 1981 planted trees than the 1980 planted trees. There was a slight advantage, as compared to the other treatments, to nutrient and water amendments in height growth during the first growing season (Appendix A, Table A-7) and at the end of the first year (Table 1-3). In the second growing season, elongation of the fertilization/irrigation 1981 planted trees was also slightly better than all other treatments (Figure 6).

For the 1981 planted trees, the average two year old total height of the fertilization/irrigation treatment units was significantly greater than all other treatment units, at both sites, except fertilization at the Basher

site (Table 1-3). Although the fertilization/irrigation treatments of the 1981 planted trees resulted in greater average height at the end of the second growing season, the relative difference for the 1981 planted trees was not as great as for the 1980 planted trees (Figure 6). Averaged over plantation sites, the 1980 planted fertilization/irrigation tree total height of 3.9 m was 2.2 m greater than the control, 1.8 m greater than the irrigation and 0.4 m greater than the fertilization treatment units. The Basher and Morrison 1981 planted fertilization/irrigation trees averaged 4.7 m, which was 0.3 m greater than the control, 0.6 m greater than irrigation and 0.1 m greater than the fertilization treatment units.

Among the 1981 planted treatment units, fertilization/irrigation average diameter of 3.2 cm for the Basher site and 3.3 cm for the Morrison site was significantly greater than all other treatments at either site, except fertilization at the Basher site. Again, the relative advantage of fertilization and irrigation to the 1981 planted trees was not as great as for the 1980 planted trees but the absolute size of the 1981 planted trees was greater than the 1980 planted trees (Figure 8).

Second Year Fertilization/Irrigation Summary - Fertilization/irrigation treatments resulted in two year old trees with greater average total height and diameter (Figures 7 and 8) than all other treatments when the trees were established with poor weed control methods (1980 planting). Average growth advantage for the 1980 planted fertilization/irrigation trees was substantially greater than the control and irrigation treatments, and slightly greater than the fertilization treatment. In contrast, the fertilization/irrigation treatments to the 1981 planted trees (good weed control) resulted in only a slight average total height or diameter gain over all other treatments (Figures 7 and 8). In some cases the site-treatment differences were not significant. The main reason for the dissimilar relative advantage of fertilization/irrigation treatment for the 1980 and 1981 planted trees (Figures 7 and 8) was the effectiveness of the establishment year weed control programs.

Third Year - Average total height for the three year old 1980 planted fertilization/irrigation treatment units was 5.8 m for the Basher site and 5.9 m for the Morrison site. The two values were not significantly different from each other (Table 1-3). At both sites, the average total height values of the fertilization/irrigation trees were significantly greater than the control and irrigation treatments but not the fertilization treatments. Average stem diameter of the Basher fertilization/irrigation trees (3.8 cm) was not significantly greater than the value for the Morrison trees (3.7 cm). As with average total height, the fertilization/irrigation treatment average diameter values were significantly greater than the control and irrigation treatment values but not significantly greater than the fertilization treatment value.

Average total height in the third year of the 1981 planted fertilization/irrigation treatment units was significantly lower at the Basher site (6.0 m) than the Morrison site (6.2 m). At both sites, the average height values for the fertilization/irrigation trees were significantly greater than all other treatments, except for fertilization at the Basher site (Table 1-3). Average stem diameter for the fertilization/irrigation trees planted at the Basher site (4.1 cm) was also significantly lower than the

trees planted at the Morrison site (4.2 cm). Compared to the other treatments, the stem diameter advantage of fertilization/irrigation was similar to the total height advantage.

Third Year Fertilization/Irrigation Summary - Fertilization/irrigation produced three year old average tree sizes that were greater than all other treatments but the relative advantage was dependent on weed control in the establishment year (Figures 7 and 8). Greatest differential values for fertilization/irrigation over the other treatments was for trees planted with poor weed control in the establishment year (1980 replications). The least differential value was obtained for the trees planted with good weed control practices (1981 plantings). In the control and irrigation treatments, weed control had a major effect on the three year old average tree height and diameter values (Table 1-3). Weed control practices also influenced these growth variables for the fertilization/irrigation trees but the differences were not as pronounced. Averaged over plantation sites, the fertilization/irrigation trees planted in 1980 were 5.9 m in height and 3.8 cm in diameter, whereas the 1981 planted trees averaged 6.1 m in height and 4.2 cm in diameter.

Fourth Year - Average total height for the four year old 1980 planted fertilization/irrigation treatment units was 6.9 m for the Basher site and 7.0 m for the Morrison site. The two values were not significantly different from each other (Table 1-3). At both sites, the average total height values of the fertilization/irrigation trees were significantly greater than all other treatments, except fertilization at both sites. Average stem diameter for the Basher fertilization/irrigation trees (4.6 cm) was significantly greater than the value for the Morrison trees (4.4). As with average total height, the fertilization/irrigation treatment average diameter values were significantly greater than all other treatment values except the Basher and Morrison fertilization treatment values.

Average four year old total height for the 1981 planted fertilization/irrigation trees was 7.4 m at both the Basher and Morrison plantation sites. These four year old trees were significantly taller than all other treatments (Table 1-3) regardless of site. Average four year old stem diameter of 5.0 cm for the Morrison fertilization/irrigation treatment was significantly greater than the Basher site value (4.8 cm). At both sites the fertilization/irrigation treatment values were significantly greater than the other treatment values, except the Basher site fertilization value.

Fourth Year Fertilization/Irrigation Summary - As with the irrigation and fertilization treatments, the absolute and relative tree growth variables for the fertilization/irrigation treatment were dependent on weed control efficiency in the establishment year (Figures 7 and 8). For the 1980 plantings, fertilization and irrigation resulted in trees which annually were taller and larger in diameter than either the control or irrigated trees. When compared to the control treatment averages, fertilization/irrigation treatment units averaged about 30% greater in the four year total height and about 45% greater in the four year stem diameter. Fertilization/irrigation of the 1980 planted trees resulted in trees similar in average size to the fertilization trees. The combination of fertilizing and irrigating the 1981 planted trees resulted in

significantly greater two, three and four year old average total height and stem diameter values than the control, irrigation and fertilization treatments. However, these 1981 planted tree differences between the fertilization/irrigation and the control or the irrigation treatments were not as large as with the 1980 plantings. After four growing seasons, the 1981 planted fertilization/irrigation treatment units averaged about 10% greater in total height and 15% greater in stem diameter, as compared to the control treatment averages.

Growth Summary

Total height and stem diameter of first rotation *Populus* hybrid trees planted on the two study sites demonstrated:

(1) There were advantages in providing good weed control in the first growing season.

(2) Two year old trees grow faster than one year old trees, two year growth rates were sustained in the third year but slowed in the fourth year.

(3) Favorable sites (Basher) resulted in trees that were somewhat larger compared to unfavorable sites (Morrison).

(4) Fertilization and fertilization/irrigation investments increased tree growth over no amendments. Irrigation had mixed results.

Averaged over the two plantation sites and all four treatments, the one year old 1980 planted trees averaged 1.0 m in height and 0.8 cm in diameter at 15 cm above ground. These values were much lower than the average total height of 1.7 m and stem diameter of 1.4 cm achieved by the one year old trees planted in 1981. Growing season conditions were slightly different and irrigation was used in the 1981 growing season but the major reason for nearly doubling the tree growth was the effectiveness of the 1981 weed control program.

All two year old trees planted in 1980 increased total height by an average of 1.8 m to a total height of 2.8 m at the end of the second growing season. Average diameter increased 1.3 cm in the second growing season to the two year total diameter of 2.1 cm. The 1981 planted trees increased total height by an average of 2.7 m to a height of 4.4 m at the end of the second growing season (when averaged over sites and all treatments). These same 1981 planted trees increased average stem diameter by 1.6 cm in the second growing season to the two year total of 3.0 cm.

The three year old 1980 planted trees continued to increase average tree size at a rate comparable to their two year old rate. Average total height increased 2.3 m in the third year and achieved an average of 5.0 m at the end of three growing seasons. All trees increased stem diameter by 1.2 cm in the third growing season to 3.2 cm at the end of three years. In contrast to the 1980 planted trees, the 1981 plantings had less height and diameter growth in the third growing season than their second growing season. Total height of all 1981 planted trees was increased an average of 1.4 m in the third year to obtain a total height of 5.8 m at the end of

three years. Average stem diameter of these same 1981 planted trees increased by 0.7 cm in the third year to the three year old average of 3.9 cm.

The 1980 plantings had, relatively, slow growth in the first year, rapid growth in the second and third years and slow growth in the fourth growing season. All 1980 planted trees exhibited a reduced fourth year growth in height and diameter. Average total height for all treatments at both sites was increased by 1.4 m in the fourth growing season to the four year old average of 6.4 m. In the fourth year, stem diameter of these same trees increased 0.8 cm to the four year old average of 4.0. The 1981 plantings had, relatively, rapid growth in years one and two, and slower growth in years three and four. All 1981 planted trees grew an average 1.2 m in total height during the fourth growing season to achieve an average of 7.0 m after four growing seasons. These same 1981 planted trees grew 0.6 cm in stem diameter during the fourth growing season to obtain an average of 4.5 cm after four years of growth. The major reason for the 0.6 m average four year old total height and 0.5 cm stem diameter advantage of the 1981 planted trees over the 1980 planted trees was the effectiveness of weed control in the establishment year.

Relative value of plantation site (favorable or unfavorable) can be evaluated by the growth of the control treatments, to some degree by irrigation or fertilization treatments but not the fertilization/irrigation treatment. The control treatment tree growth was dependent on inherent soil fertility and soil water. The irrigation treatment was one that maintained non-limiting soil water conditions, regardless of site, but the available soil nutrients were site dependent. The fertilization treatment was one that maintained non-limiting soil nutrient conditions, regardless of site, but available water was site dependent. The fertilization/irrigation treatment was one in which both soil nutrients and soil water were maintained at non-limiting growth conditions.

In the first growing season, the Morrison control trees were significantly taller and larger in diameter than the Basher control trees for both the 1980 and 1981 planted trees (Table 1-3). The two year old 1980 planted trees at the Basher site were significantly larger in size than the trees growing at the Morrison site. However, for the 1981 planted trees, the two year old control trees at the Morrison site were significantly larger in size than the trees planted at the Basher site (Table 1-3). After three growing seasons, the Basher control trees planted in 1980 averaged 4.2 m tall and 2.7 cm in diameter. These values were significantly greater than the average total height (3.9 m) and diameter (2.4 cm) for the trees growing at the Morrison site. In contrast, there were no site differences in control three year old average total height and diameter for the 1981 planted trees. The Basher control trees planted in 1980 averaged 5.4 m in height and 3.5 cm in diameter at the end of the first rotation. The four year old Morrison 1980 planted control trees averaged 5.2 m in total height and 3.3 cm in diameter. The average total height site difference was not significant but the site difference for average stem diameter was significant (Table 1-3). The control trees planted at the Basher and Morrison sites in 1981 obtained the same average four year old total height and stem diameter values (Table 1-3). Good weed control in the establishment year for the 1981 planted trees substantially increased the average

four year old tree size variables over the values measured for the trees planted with poor weed control (1980 plantings). Averaged over both sites, the 1980 planted control treatments were 5.1 m in height and 3.4 cm in diameter, and the 1981 planted control treatments were 6.8 m in height and 4.2 cm in diameter.

Irrigation water was applied to one year old trees in 1981. The water amendments did not increase the one year old average total height or stem diameter compared to control trees at either site (Table 1-3). The trees planted in 1980 were not irrigated in the first growing season but they were in the subsequent growing seasons. The Basher site irrigation two year old 1980 planted trees were taller (2.6 m) and larger in stem diameter (2.0 cm) than the control trees which had an average total height and stem diameter of 1.9 and 1.5 cm, respectively (Table 1-3). The Morrison site irrigation two year old trees planted in 1980 were about the same height and diameter as the control trees (Table 1-3). The irrigation two year old 1981 planted trees also had mixed relative tree size values, when compared to control, depending on site and specific size variable (Table 1-3). Water amendments in the third year of the 1980 planted trees continued to increase the total height and diameter of the irrigation trees over the control treatment values at the Basher site, but not at the Morrison site.

Irrigation treatment units of the 1981 planted trees continued to have mixed results in the third growing season. Compared to the control trees, irrigation to the 1981 planted trees resulted in trees that were not as tall and had smaller diameters at the Basher site, and the irrigation trees at the Morrison site had the same three year old average height but larger average diameter than the control trees. Reasons for the lower average size of the irrigation Basher 1981 planted trees may be due to one replication that is located in a depression and poor internal soil drainage could be restricting tree growth in that replication.

The four year old irrigation trees planted at the Basher site in 1980 averaged 6.2 m in height and 4.0 cm in diameter. At the Morrison site, the four year old 1980 planted irrigation treatment units averaged 5.6 m in height and 3.6 cm in diameter. The differences between the two sites were significant. Irrigation, at each site, resulted in average four year old tree sizes that were larger than the control treatment. First rotation growth gains from irrigation, as compared to the control, for the trees planted in 1980, was about 10% at the Morrison site and 15% at the Basher site. The 1981 planted four year old control and irrigation trees were about 20% larger in average total height and stem diameter than the 1980 planted control and irrigation trees. In addition, there were no sustained differences between the 1981 control and irrigation trees (Table 1-3). For this study, weed control in the establishment year appeared to be more critical in determining first rotation growth rates than available water.

Fertilization increased the one year old total height and stem diameter over the controls for the 1980 planted trees at both sites (Table 1-3). In contrast, tree height and diameter values for the fertilized 1981 planted trees were similar and in some cases lower than the control trees.

A major advantage of fertilization to the 1980 planted trees was evident in the second growing season. The one year old total height for the Basher

fertilization trees was 0.5 m greater than the control trees. At age two the fertilization Basher trees were 3.5 m in height or 1.6 m taller than control trees (Table 1-3). At the Morrison site one year old fertilization trees were 0.3 m taller than the control trees, and the two year old trees averaged 3.4 m in height which was 1.9 m greater than the two year old control trees (Table 1-3). Stem diameter for the two year old trees paralleled the total height values with the fertilization trees at the Basher and the Morrison site and was considerably larger than the control trees (Table 1-3). After two growing seasons, the 1981 planted fertilization trees were significantly taller and larger in diameter than the control trees at the Basher site, and significantly larger in diameter but not in total height, compared to the control trees, at the Morrison site (Table 1-3).

The fertilization trees planted in 1980 maintained their growth advantage over the control trees in the third growing season. The fertilization trees at the Basher site were 5.7 m tall or 1.6 m greater than the control trees (Table 1-3). They were also 3.7 cm in diameter or 1.0 cm greater than the control tree average. At the Morrison site, the fertilization trees were 5.8 m in height and 3.6 cm in diameter (Table 1-3). These values were 1.9 m taller and 1.1 cm larger in diameter than the control tree averages. Fertilization to trees planted with good weed control in the establishment year (1981) did not result in the same growth advantage over the control as was evident with the 1980 planted treatments. Average total height and diameter values of the 1981 planted fertilization trees growing at the Basher site were significantly greater than the control values but there were no significant control - fertilization differences at the Morrison site (Table 1-3).

At the end of the first rotation, fertilization of the 1980 planted trees at the Basher site produced trees that averaged 7.4 m in height and 4.6 cm in diameter. Fertilization at the Morrison site resulted in trees which averaged 6.9 m in total height and 4.2 cm in diameter at four years of age. The Basher site fertilization units averaged significantly larger total height and diameter values than the Morrison fertilization units. In all cases, fertilization of the 1980 planted trees resulted in four year old tree size values significantly larger than control and irrigation, and about the same as the fertilization/irrigation. The first rotation gains in average size for fertilization, as compared to control, was about 35% for the trees planted in 1980. For the trees planted in 1981, fertilization resulted in the same average four year old total height at both the Basher and Morrison sites (7.1 m) but the Basher fertilization average stem diameter value (4.8 cm) was significantly greater than the Morrison average value (4.6 cm). In all cases the four year old 1981 planted fertilization units averaged significantly larger than the control units and significantly smaller than the fertilization/irrigation units.

The Basher fertilization units were significantly greater in average total height and stem diameter than the irrigation units. There were no significant differences in the irrigation vs fertilization treatments at the Morrison site, and little difference in height and stem diameter between four year old 1980 and 1981 planted fertilized trees.

The 1981 planted control trees, however, were substantially larger than the 1980 planted control trees (poor weed control). Weed control was responsible for the 1981 planted fertilization trees having an 8% growth advantage over the 1981 planted control trees, while of the 1980 planted fertilization trees had a 35% growth advantage over 1980 planted control trees (Table 1-3).

Combined amendments of fertilization and irrigation were applied in 1981 to the one year old 1981 planted trees and the two year old 1980 planted trees. The treatment combination resulted in one year old trees at the Basher site being taller and larger in diameter than the other treatments. There were no apparent differences among treatments at the Morrison site for the one year old trees (Table 1-3).

Fertilization/irrigation of the two year old 1980 plantings resulted in trees that were the tallest and largest in diameter at both sites (Table 1-3). The Basher fertilization/irrigation trees grew from an average one year old total height of 1.1 m to 3.7 m at age two. Stem diameter increased from 0.9 cm to 2.5 cm between ages one and two. The Morrison fertilization/irrigation trees increased in average total height from 1.1 m at age one to 4.0 m at two years of age. Average stem diameter of these trees increased from an average of 0.9 cm for one year old trees to 2.7 cm at two years of age.

The two year old fertilization/irrigation trees planted in 1981 were also the tallest and largest in diameter at both the Basher and Morrison site. The Basher fertilization/irrigation trees grew an average of 2.8 m in height and 1.7 cm in diameter in the second growing season to a total height of 4.7 m and diameter of 3.1 cm after two years of age. The Morrison fertilization/irrigation trees grew an average of 3.0 m in height and 1.5 cm in diameter in the second year to a total height of 4.7 m and diameter of 3.1 cm after two years of age (Table 1-3).

The tallest and largest treatment values for the three year old trees were on the fertilization/irrigation units, regardless of year of planting. The three year old 1980 planted fertilization/irrigation trees at the Basher and Morrison sites were not significantly different in either total height or stem diameter. Averaged over plantation sites, the 1980 planted fertilization/irrigation units were 5.9 m and 4.5 cm in total height and diameter, respectively. At each plantation site, these fertilization/irrigation unit averages were significantly greater than either the control or irrigated units but not significantly different from the fertilization units. The 1981 planted fertilization/irrigation treatments were significantly taller and larger in diameter at the Morrison site than at the Basher site but the differences were only 0.2 m in total height and 0.2 cm in stem diameter. The 1981 planted three year old Basher fertilization/irrigation unit averages of 6.0 m in total height and 4.1 cm in stem diameter were significantly greater than the control and irrigation treatment averages but not significantly different from the fertilization treatment averages. For the 1981 planted trees at the Morrison site, the fertilization/irrigation average total height and diameter values were significantly greater than the control and fertilization values but not significantly different than the irrigation values.

At the end of the first rotation, fertilization/irrigation resulted in four year old trees with larger average total height and stem diameter than the control or irrigation treatments, regardless of planting year or plantation site. Combined fertilization and irrigation did not result in average four year old tree size values significantly greater than fertilization, except for stem diameter of the 1981 plantings at the Morrison site. The four year old total height of the fertilization/irrigation trees averaged 6.9 and 6.8 m at the Basher site, and 7.0 and 7.4 m at the Morrison site for the trees planted in 1980 and 1981, respectively. Stem diameter for the four year old fertilization/irrigation units averaged 4.6 and 4.8 cm at the Basher site, and 4.4 and 5.0 cm at the Morrison site for the 1980 and 1981 plantings, respectively. As compared to the control treatments for each year of establishment, fertilization/irrigation increased average four year old trees size values about 35% for the 1980 planting and about 12% for the 1981 planting. As with the other treatment comparisons the apparent fall down in differential control-to-other-treatment responses between the 1980 and 1981 plantings was mainly due to the control unit growth rates with good and poor weed control in the year of establishment.

Yield Summary

Field and oven dry biomass yields above a 15 cm stump height of individual Populus trees, by selected components, were calculated from equations and summarized for all living trees per site-replication-treatment plots. The equations were developed from trees collected from the destructive sample units in each plot. Field weight values (green total tree, excluding leaves) were for trees collected in November-December from the plantations. Oven dry values were determined by the methods described by Bowersox and Murphey (1975) in which the various components were dried in a forced air oven at 105°C until weight loss stabilized. The equations for determining one, two, three and four year old field weight of total tree and oven dry total tree, mainstem wood, bark, and branches are listed in Tables 2-7, 8, 9 and 10. Equations for predicting weight of one, two, three and four year old oven dry leaves in September are given in Table 2-11. In addition, all living continuous inventory trees on each treatment unit were harvested at first rotation age of four years. Field weight for each living continuous inventory tree per treatment unit was measured to the nearest 20 g, immediately after cutting. Individual total tree field weight values for all living trees were summarized per plot.

Biomass yields were estimated three ways: 1) equation predicted field, 2) actual field and 3) adjusted OD weights. Each year about 120 trees per planting year-site-treatment combination were destructively sampled and weighed (total tree field weight). They were then debarked, debranched and oven dried to determine OD weight of wood, bark and branchwood. The data were used to determine mathematical relationships between measured biomass weights (total tree field weight and OD wood, bark and branchwood weights) and total height and stem diameter. These relationships were used to develop equations to predict field weights given age, height, diameter, site and management strategy for any given tree. The four year old equation predicted and actual field weight values for each site-treatment combination were compared. Most of the predicted values were within ± 3% of actual values but some were as much as ± 10% of actual values.

Table 2-7. Intercepts (b_0), regression coefficients (b_1) standard deviations (S) and fraction of explained variation (R^2) for equations[1/] to predict field weight (green), oven dry mainstem wood, oven dry bark, oven dry buds, and oven dry total tree (excluding leaves) for one year old trees, by treatment.

Y variable	N	b_0	b_1	S	R^2
Field Weight-Total Tree (g)					
Control	87	7.74	33.2	11.0	98%
Irrigation	86	8.80	32.2	14.0	97%
Fertilization	89	4.14	32.5	13.0	95%
Fertilization/ Irrigation	83	8.28	31.7	13.0	97%
Oven Dry Mainstem Wood (g)					
Control	87	0.92	9.0	3.0	89%
Irrigation	86	0.82	8.8	2.0	99%
Fertilization	89	0.11	9.2	3.0	97%
Fertilization/ Irrigation	83	1.38	8.6	4.0	97%
Oven Dry Bark (g)					
Control	87	2.73	3.8	2.0	95%
Irrigation	86	2.99	3.4	2.0	96%
Fertilization	89	1.60	4.3	2.0	94%
Fertilization/ Irrigation	83	2.90	3.4	3.0	88%
Oven Dry Buds (g)					
Control	87	0.58	0.3	0.4	77%
Irrigation	86	0.49	0.2	0.3	79%
Fertilization	89	0.26	0.4	0.2	90%
Fertilization/ Irrigation	83	0.42	0.3	0.3	74%
Oven Dry Total Tree (g)					
Control	87	4.15	13.0	4.0	98%
Irrigation	86	4.30	12.4	4.0	98%
Fertilization	89	1.75	13.9	5.0	97%
Fertilization/ Irrigation	83	4.70	12.2	6.0	95%

[1/] $Y = b_0 + b_1 (D^2Ht)$, where Y is weight/tree above 15 cm stump in grams, D is green outside bark diameter at 15 cm above ground in centimeters, and Ht is total tree height above ground in meters.

Table 2-8. Regression coefficients (b_1) standard deviations (S) and fraction of explained variation (R^2) for equations[1/] to predict field weight (green), oven dry mainstem wood, oven dry mainstem bark, oven dry branches and oven dry total tree (excluding leaves) for two year old trees, by treatment.

Y variable	N	b_1	S	R^2
Field Weight-Total Tree (g)				
Control	115	28.8	117	98%
Irrigation	119	28.7	174	96%
Fertilization	112	27.5	148	99%
Fertilization/ Irrigation	114	28.0	156	99%
Oven Dry Mainstem Wood (g)				
Control	115	8.6	20	98%
Irrigation	119	8.3	25	99%
Fertilization	112	8.0	40	99%
Fertilization/ Irrigation	114	8.3	46	99%
Oven Dry Mainstem Bark (g)				
Control	115	8.8	9	99%
Irrigation	119	8.6	11	98%
Fertilization	112	8.5	13	99%
Fertilization/ Irrigation	114	8.4	16	98%
Oven Dry Branches (g)				
Control	115	2.6	25	92%
Irrigation	119	2.8	30	89%
Fertilization	112	2.8	38	91%
Fertilization/ Irrigation	114	2.5	31	93%
Oven Dry Total Tree (g)				
Control	115	14.0	45	99%
Irrigation	119	13.7	59	98%
Fertilization	112	13.2	70	99%
Fertilization/ Irrigation	114	13.2	70	99%

[1/] $Y = b_1 (D^2 Ht)$ for all variables except mainstem bark which was $Y = b_1 (D\ Ht)$. Y is weight/tree above 15 cm stump in grams, D is green outside bark diameter at 15 cm above ground in centimeters, and Ht is total tree height above ground in meters.

Table 2-9. Regression coefficients (b_1) standard deviations (S) and fraction of explained variation (R^2) for equations[1/] to predict field weight (green), oven dry mainstem wood, oven dry mainstem bark, oven dry branches, and oven dry total tree (excluding leaves) for three year old trees, by treatment.

Y variable	N	b_1	S	R^2
Field Weight-Total Tree (g)				
Control	109	25.7	305	98%
Irrigation	110	27.3	328	98%
Fertilization	117	26.5	284	99%
Fertilization/ Irrigation	105	26.1	438	99%
Oven Dry Mainstem Wood (g)				
Control	109	8.19	72	99%
Irrigation	110	8.59	70	99%
Fertilization	117	8.75	99	99%
Fertilization/ Irrigation	105	8.45	123	99%
Oven Dry Mainstem Bark (g)				
Control	109	9.02	26	98%
Irrigation	110	8.64	20	99%
Fertilization	117	9.20	30	99%
Fertilization/ Irrigation	105	8.75	32	99%
Oven Dry Branches (g)				
Control	109	2.40	86	88%
Irrigation	110	2.33	69	90%
Fertilization	117	2.48	61	96%
Fertilization/ Irrigation	105	2.25	86	94%
Oven Dry Total Tree (g)				
Control	109	12.6	146	99%
Irrigation	110	12.9	128	99%
Fertilization	117	13.2	146	99%
Fertilization/ Irrigation	105	12.4	198	99%

1/ $Y = b_1 (D^2Ht)$ for all variables except mainstem bark which was $Y = b_1 (D\ Ht)$. Y is weight/tree above 15 cm stump in grams, D is green outside bark diameter at 15 cm above ground in centimeters, and Ht is total tree height above ground in meters.

Table 2-10. Regression coefficients (b_1) standard deviations (S) and fraction of explained variation (R^2) for equations[1/] to predict field weight (green), oven dry mainstem wood, oven dry mainstem bark, oven dry branches, and oven dry total tree (excluding leaves) for four year old trees, by treatment.

Y variable	N	b_1	S	R^2
Field Weight-Total Tree (g)				
Control	112	26.7	528	99%
Irrigation	110	27.8	667	99%
Fertilization	115	25.3	1266	99%
Fertilization/ Irrigation	115	26.8	942	99%
Oven Dry Mainstem Wood (g)				
Control	112	8.75	184	99%
Irrigation	110	9.33	244	99%
Fertilization	115	8.65	506	98%
Fertilization/ Irrigation	115	9.14	316	99%
Oven Dry Mainstem Bark (g)				
Control	112	10.2	39	99%
Irrigation	110	10.5	60	98%
Fertilization	115	11.1	80	99%
Fertilization Irrigation	115	10.9	87	98%
Oven Dry Branches (g)				
Control	112	2.63	106	97%
Irrigation	110	2.49	220	91%
Fertilization	115	2.04	177	96%
Fertilization/ Irrigation	115	1.98	176	96%
Oven Dry Total Tree (g)				
Control	112	13.1	259	99%
Irrigation	110	13.4	308	99%
Fertilization	115	12.2	696	98%
Fertilization/ Irrigation	115	12.7	439	99%

[1/] $Y = b_1 (D^2Ht)$ for all variables except mainstem bark which was $Y = b_1 (D\ Ht)$. Y is weight/tree above 15 cm stump in grams, D is green outside bark diameter at 15 cm above ground in centimeters, and Ht is total tree height above ground in meters.

Table 2-11. Equations[1/] for predicting the oven dry September foliage weight of individual trees, by tree age, for the four treatments.

Tree age	Treatment	N[2/]	b_0[3/]	b_1[4/]	X[5/]	S[6/]	R^2 [7/]
One Year Old							
	Control	88	3.1	13.7	d ht	3.2	96%
	Irrigation	79	3.4	12.8	d ht	4.8	92%
	Fertilization	76	4.4	12.1	d ht	5.2	85%
	Fertilization/ Irrigation	76	2.5	12.0	d ht	4.0	93%
Two Year Old							
	Control	115	-	3.98	d^2 ht	43.1	90%
	Irrigation	119	-	3.81	d^2 ht	49.6	84%
	Fertilization	112	-	3.74	d^2 ht	51.3	91%
	Fertilization/ Irrigation	114	-	3.91	d^2 ht	38.4	93%
Three Year Old							
	Control	109	-	1.81	d^2 ht	98.8	75%
	Irrigation	110	-	2.25	d^2 ht	67.5	90%
	Fertilization	117	-	1.91	d^2 ht	91.4	87%
	Fertilization/ Irrigation	105	-	1.75	d^2 ht	82.7	91%
Four Year Old							
	Control	112	-	1.44	d^2 ht	150.0	86%
	Irrigation	110	-	1.44	d^2 ht	142.0	89%
	Fertilization	115	-	1.16	d^2 ht	137.0	92%
	Fertilization/ Irrigation	115	-	1.14	d^2 ht	86.7	97%

1/ Foliage (g) = $b_0 + b_1$ (X) for one year old trees and Foliage (g) = b_1 (X) for two, three and four year old trees.

2/ Number of observations in the equation.

3/ Y intercept.

4/ Line slope.

5/ Diameter in cm at 15 cm above ground and total tree height in meters.

6/ Standard deviation of Y about regression line.

7/ Fraction of explained variation.

Therefore the predicted four year old OD values were adjusted according to the actual vs predicted ratios to determine the OD mainstem wood, mainstem bark, branchwood and total tree harvest potential. These adjusted OD yield values were used to estimate the energy and fuel potential of the various production sytems.

Predicted Yields

Planting Year Effects - The trees planted in 1980 were established with poor weed control measures whereas the trees planted in 1981 had good weed control practices. Averaged over both sites and all management strategies, the 1980 planted trees accumulated 248, 4,138, 15,790 and 28,730 ODkg/ha of mainstem and branch material after one, two, three and four growing seasons, respectively. Total tree accumulated yields from the 1981 plantings, averaged over both sites and all management strategies, were 1,241, 13,135, 24,000 and 37,447 ODkg/ha after one, two, three and four growing seasons, respectively. As the result of a good weed control program in the establishment year, yields of the 1981 planted trees were greater than those of the 1980 planted trees (poor weed control) by a factor of 5, 2.6, 1.5 and 1.3 after one, two, three and four growing seasons, respectively.

Averaged over both sites and all management strategies, the annual production of total tree biomass increased with age. In the first growing season the 1980 planted trees produced 248 ODkg/ha of biomass. In the second growing season, the 1980 planted production of 3,890 ODkg/ha was 16 times greater than the first year value. Third year production of 11,652 ODkg/ha for the 1980 planted trees was 47 times greater than the first year and 3.0 times greater than the second year biomass increments. In the final year of the first rotation these 1980 planted trees produced 12,940 ODkg/ha of biomass. This fourth year biomass increment was 52, 3.3 and 1.1 times greater than the amounts produced in the first, second and third growing seasons, respectively

The 1981 planted trees produced 1,241 ODkg/ha of total tree biomass in the first growing season, averaged over both sites and all management strategies. Second year production of 9,864 ODkg/ha for the 1981 planted trees was 7.9 times greater than the first year value. In the third year, these 1981 planted trees produced 12,864 ODkg/ha and this value was 10.4 times greater than the first year and 1.3 times greater than the second year biomass production values. Biomass increment during the fourth year was 13,447 ODkg/ha for the 1981 planted trees. This final growing season of the first rotation production value was 10.8, 1.36 and 1.05 times greater than the first, second and third year production values, respectively.

Annual biomass increment appears to be reaching a maximum for the trees established in 1980 and 1981. Apparently, the planting density of one tree per $0.48m^2$ has captured the site potential in the designed four year rotation schedule. However, the 1981 planted trees produced more biomass in each of the first rotation growing seasons than was measured for the 1980 planted trees. The major reason for the difference in the four year biomass yield values for 1980 and 1981 planted trees was the biomass production rates in years one and two. The poor weed control methods for

the 1980 planted trees resulted in an average of 248 and 3890 ODkg/ha of total tree biomass in years one and two, respectively. In contrast, the good weed control program used for the 1981 planted trees resulted in an average of 1,241 and 9,864 ODkg/ha of biomass in years one and two, respectively. These differences represent good (1981 trees) vs poor (1980 trees) weed control gains of 5.0 for the first and 2.5 for the second growing seasons. The annual production gains of the 1981 planted trees over the 1980 planted trees dropped to 1.1 for the third and 1.04 for the fourth growing seasons.

Site Effects - The biomass production comparisons between the two plantation sites (Basher and Morrison) can be evaluated by the yields of the control treatments, to some degree by irrigation or fertilization treatments, but not the fertilization/irrigation treatment. Rationales for the comparative limits have been previously discussed.

In the first growing season there were no significant site yield advantages for the control, irrigation or fertilization treatments, regardless of whether the trees were planted in 1980 or 1981 (Table 2-12). At the end of the second growing season, there were no significant site advantages in accumulated biomass variables for either the control or fertilization 1980 planted or 1981 planted trees (Table 2-13). The 1980 planted irrigation trees growing at the Basher site had accumulated significantly more total biomass than the 1980 planted irrigation trees growing at the Morrison site, but the significant difference between sites was reversed for the 1981 planted accumulated two year old yields.

Biomass yields for the Basher and Morrison sites were similar at the end three growing seasons. Regardless of year of establishment, there were significant site differences in the total tree OD biomass yields for the control, fertilization or fertilization/irrigation treatments, but there was a significant site difference in the irrigation treatment (Table 2-1 Site effect on the three year old irrigation total tree yields was the s as for the two year old values. The irrigation 1980 planted trees at th Basher site had greater three year old OD biomass yields than the Morris site. However, the site advantage was reversed for the 1981 plantings b it was not significant (Table 2-14).

After four growing seasons for the 1980 planted replications the Basher control accumulated total biomass of 21,702 ODkg/ha was not significantl greater than the 18,736 kg/ha for the Morrison control. The Basher fertilization average total yield of 34,091 ODkg/ha was not significantl greater than the 29,506 ODkg/ha average for the Morrison fertilization trees. As with the two and three year old 1980 planted trees, there was significant site difference for the irrigation trees. The Basher irrigation trees had accumulated an average 31,499 ODkg/ha after three years which was significantly greater than the 21,487 ODkg/ha average val for the Morrison irrigation trees (Table 2-15).

Four years of growth on the 1981 planted replications resulted in the Basher and Morrison control treatment units accumulating 34,314 and 31,9 (respectively) ODkg/ha of total biomass (Table 2-15). These site differences, and the difference for the fertilization and fertilization/ irrigation treatment units, were not significant. In contrast to the 198

Table 2-12. Average[1/] one year old total tree field weight (green) and oven dry weight, and oven dry mainstem wood, bark, branches and leaves at the end of the growing season. These values were calculated from the equations presented in Tables 2-7 and 2-11 for each of the surviving trees per plot and summarized per plot, with six plots (1980 and 1981 replications) per site per treatment.

Plantation Site	Treatment	Total tree		Oven Dry			
		Field	Oven Dry	Mainstem Wood	Mainstem Bark	Branches[3/]	Leaves
		kg/ha					
1980 Planting							
Basher	Control	347a	155a	73a	84a	0	167a
	Irrigation[2/]	480a	201a	102a	99a	0	209ab
	Fertilization	802b	343b	205b	137b	0	326d
	Fertilization/Irrigation[2/]	698b	295b	174b	121b	0	250bc
Morrison	Control	459a	200a	102a	99a	0	219ab
	Irrigation[2/]	360a	154a	71a	84a	0	169a
	Fertilization	707b	302b	179b	123b	0	304cd
	Fertilization/Irrigation[2/]	796b	332b	201b	131b	0	273bcd
1981 Planting							
Basher	Control	2402a	962a	626a	339a	0	674a
	Irrigation	2315a	909a	600a	311a	0	627a
	Fertilization	2318a	991a	630a	359a	0	662a
	Fertilization/Irrigation	3013a	1189a	798a	393a	0	721a
Morrison	Control	2547a	1019a	665a	357a	0	711a
	Irrigation	2190a	859a	568a	293a	0	600a
	Fertilization	1758a	751a	474a	275a	0	529a
	Fertilization/Irrigation	2154a	856a	566s	291a	0	558a

1/ Treatment means within and between plantation sites - by planting year - with a common letter within components are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance.

2/ Includes trees of the 1980 planted replications that were not irrigated because the system was not in place.

3/ The one year old trees had no branches.

Table 2-13. Average[1/] two year old total tree field weight (green) and oven dry weight, and oven dry mainstem wood, bark, branches and leaves at the end of the growing season. These values were calculated from the equations presented in Tables 2-8 and 2-11 for each of the surviving trees per plot and summarized per plot, with six plots (1980 and 1981 replications) per site per treatment.

Plantation Site	Treatment	Total tree		Oven Dry			
		Field	Oven Dry	Mainstem Wood	Mainstem Bark	Branches	Leaves
		kg/ha					
1980 Planting							
Basher	Control	3520a	1711a	1052a	535a	318a	1205a
	Irrigation[2/]	7980b	3809b	2300b	944b	779b	1620b
	Fertilization	13287cd	6378cd	3875cd	1393cd	1334cd	2211c
	Fertilization/Irrigation[2/]	14408d	6792d	4291d	1437cd	1281cd	1813b
Morrison	Control	1970a	957a	589a	376a	178a	1088a
	Irrigation[2/]	2356a	1125a	679a	390a	230a	1055a
	Fertilization	10425bc	5004bc	3040bc	1198bc	1046bc	1896b
	Fertilization/Irrigation[2/]	15529d	7321d	4625	1555d	1381d	1900b
1981 Planting							
Basher	Control	19244ab	9355ab	5753ab	1957ab	1737ab	2839ab
	Irrigation	14931a	7127a	4302a	1611a	1457a	2302a
	Fertilization	26320c	12634bc	7676bc	2444b	2642c	3734c
	Fertilization/Irrigation	28367c	13373c	8449c	2494b	2523c	3039b
Morrison	Control	22870bc	11117bc	6837bc	2264b	2065abc	3217bc
	Irrigation	23753bc	11339bc	6845bc	2188b	2317bc	3058b
	Fertilization	23278bc	11173bc	6789bc	2177b	2336bc	3294bc
	Fertilization/Irrigation	27496c	12963bc	8190c	2372b	2445c	2913ab

[1/] Treatment means within and between plantation sites - by planting year - with a common letter within components are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance.

[2/] Trees were not irrigated in the first growing season only.

Table 2-14. Average[1/] three year old total tree field weight (green) and oven dry weight, and oven dry mainstem wood, bark, branches and leaves at the end of the growing season. These values were calculated from equations presented in Tables 2-9 and 2-11 for each of the surviving trees per plot and summarized per plot, with six plots (1980 and 1981 replications) per site per treatment.

Plantation Site	Treatment	Total tree		Oven Dry			
		Field	Oven Dry	Mainstem Wood	Mainstem Bark	Branches	Leaves
		kg/ha					
1980 Planting							
Basher	Control	21139a	10364a	6737a	2106a	1974a	2328abc
	Irrigation[2/]	35203b	16635b	11077b	2819b	3005b	3260d
	Fertilization	43806bc	21821b	14464bc	3527b	4100c	3173d
	Fertilization/Irrigation[2/]	46520c	22102b	15061b	3475b	4010c	3080d
Morrison	Control	14765a	7239a	4705a	1763a	1379a	2140ab
	Irrigation[2/]	17589a	8311a	5534a	1704a	1501a	2031a
	Fertilization	37904bc	18881b	12516bc	3237b	3547bc	2750bcd
	Fertilization/Irrigation[2/]	44135bc	20968b	14289bc	3426b	3805bc	2918cd
1981 Planting							
Basher	Control	40398a	19806a	12874a	3546ab	3773ab	3285a
	Irrigation	39336a	18587a	12377a	3218a	3357a	3577ab
	Fertilization	55759b	27774b	18411b	4360c	5218d	4037ab
	Fertilization/Irrigation	57848b	27484b	18729b	4278c	4987cd	3836ab
Morrison	Control	41663a	20426a	13277a	3731abc	3891abc	3360a
	Irrigation	51742ab	24450ab	16281ab	3811abc	4416abcd	4330b
	Fertilization	49496ab	24654ab	16343ab	3991bc	4632bcd	3583ab
	Fertilization/Irrigation	60663b	28821b	19640b	4356c	5230d	4033ab

[1/] Treatment means within and between plantation sites - by planting year - with a common letter within components are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance.

[2/] Trees were not irrigated in the first growing season only.

Table 2-15. Average[1/] four year total tree field weight (green) and oven dry weight, and oven dry mainstem wood, bark, branches and leaves at the end of the growing season. These values were calculated from equations[2/] presented in Tables 2-10 and 2-11 for each of the surviving trees per plot and summarized per plot. There where three plots (1980 replications) per site per treatment.

Plantation Site	Treatment	Total tree		Oven Dry			
		Green	Oven Dry	Mainstem Wood	Mainstem Bark	Branches	Leaves
		kg/ha					
1980 Planting							
Basher	Control	44231a	21702a	14495a	3825a	4357ab	2386ab
	Irrigation[2/]	65348bc	31499b	21932bc	5064b	5853c	3385c
	Fertilization	70696bc	34091b	24171bc	5937b	5700c	3241bc
	Fertilization/Irrigation[2/]	75759bc	35901b	25837bc	5712b	5597bc	3223bc
Morrison	Control	38188a	18736a	12513a	3672a	3762a	2059a
	Irrigation[2/]	44577a	21487a	14961a	3816a	3993abc	2309a
	Fertilization	61189b	29506b	20920b	5500b	4934abc	2806abc
	Fertilization/Irrigation[2/]	77899c	36915b	26567c	5972b	5755c	3114c
1981 Planting							
Basher	Control	69938ab	34314ab	22920ab	5660a	6889b	3772ab
	Irrigation	63896a	30799a	21444a	5432a	5723a	3310a
	Fertilization	83962cd	40488cd	28706cd	6860c	6770ab	3850ab
	Fertilization/Irrigation	89921d	42612cd	30667d	6793c	6643ab	3825ab
Morrison	Control	65032a	31907ab	21312a	5547a	6406ab	3507ab
	Irrigation	77410bc	37313bc	25980bc	5999ab	6933b	4010b
	Fertilization	77672bc	37454bc	26556bc	6616bc	6262ab	3561ab
	Fertilization/Irrigation	94297d	44685d	32159d	7016c	6968b	4011b

[1/] Treatment means within and between plantation sites with a common letter within components are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance.

[2/] Trees were not irrigated in the first growing season only.

planted replications, which suggested a significant irrigation advantage in biomass productivity at the Basher site, the estimates for the 1981 planted replications suggested significantly lower accumulated four year old total biomass at the Basher site (30,799 ODkg/ha) than at the Morrison site (37,313 ODkg/ha).

Irrigation Effects - Irrigation was applied to one year old trees in 1981. The water amendments did not increase the biomass production over the control values at either site. The trees planted in 1980 were not irrigated in their first growing season, but they were irrigated in the second year. This irrigation program resulted in the irrigated trees at the Basher site accumulating significantly more total biomass than the control trees, but there was no significant difference between the irrigation and control trees at the Morrison site (Table 2-13). At the end of two growing seasons, the 1981 planted irrigation trees growing at the Basher site had accumulated significantly lower amounts of biomass than the Basher control trees, and there were no two year old differences between the 1981 planted control and irrigation trees growing at the Morrison site (Table 2-13). In addition, there were no significant differences between the two year old total accumulated OD biomass for Basher irrigation (5,468 ODkg/ha) and control (5,533 ODkg/ha) or the Morrison irrigation (6.232 ODkg/ha) and control (5,537 ODkg/ha).

Three years after planting the 1980 replications at the Basher site, the irrigation trees accumulated 16,635 ODkg/ha of total biomass which was significantly greater than the 10,364 ODkg/ha that the control trees had accumulated (Table 2-14). At the Morrison site, the accumulated biomass of the irrigation trees averaged 8,311 ODkg/ha and was not significantly greater than the control tree value of 7,239 ODkg/ha (Table 2-14). Total tree OD yields of the irrigated three year old 1981 planted trees were not significantly different from the control tree yields at either the Basher or Morrison site (Table 2-14).

At the end of the first rotation for the 1980 planted trees, irrigation resulted in significantly more biomass than the control at the Basher site but not at the Morrison site (Table 2-15). Irrigation to the trees growing at the Basher site produced four year old trees that had accumulated 31,499 ODkg/ha and the control trees had accumulated 21,702 ODkg/ha. The four year irrigation trees at the Morrison site accumulated 21,487 ODkg/ha of biomass and the control trees accumulated 18,736 ODkg/ha. Amount of total biomass accumulated at the end of the first rotation for the 1981 planted irrigation treatment units was greater, when averaged over plantation sites, than obtained for the 1980 irrigation treatment units. However, the irrigation treatment advantage over control treatment for the 1981 planted replications was the antithesis of the 1980 planted irrigation-control treatment differentials. The four year old irrigation production value for the trees planted at the Basher site in 1981 of 30,799 ODkg/ha of total biomass was significantly lower than the control tree value of 34,314 ODkg/ha; and the Morrison irrigation treatment value of 37,313 ODkg/ha was significantly greater than the Morrison control treatment average of 31,907 ODkg/ha (Table 2-15).

Fertilization Effects - Fertilization significantly increased the amount of biomass produced in the first growing season for the 1980 trees planted at

both sites, when compared to the control production values (Table 2-12). In the second growing season, average total accumulated biomass for the 1980 planted fertilization trees was 6,378 and 5,004 ODkg/ha for the Basher and Morrison sites, respectively. These values were significantly greater than the control values of 1,711 and 957 for the Basher and Morrison sites, respectively (Table 2-13). The two year old 1981 planted fertilization trees growing at the Basher site had accumulated 12,634 ODkg/ha which was not significantly greater than the control accumulated biomass of 9,355 ODkg/ha (Table 2-13). There was no significant difference between the control and fertilization treatment yields for the 1981 planted trees growing at the Morrison site (11,117 and 11,173 ODkg/ha, respectively).

Accumulated three year old yields for the 1980 planted fertilization trees were significantly greater than the control values. At the Basher site, the three year old fertilization values were 21,821 ODkg/ha compared to 10,364 ODkg/ha for the control treatment (Table 2-14). The three year old total OD biomass above a 15 cm stump for the Morrison fertilization trees was 18,881 ODkg/ha whereas the control treatment value was 7,239 ODkg/ha (Table 2-14). The OD three year old yields for the fertilization 1981 planted trees were significantly greater than the control treatment values at the Basher site but not at the Morrison site (Table 2-14). There was no significant difference in OD biomass for the fertilization trees growing at the Basher site (average of 27,774 ODkg/ha) and the fertilization trees growing at the Morrison site (average of 24,654 ODkg/ha).

The accumulated yields for the fertilization treatment were significantly greater than the control treatment values at both sites (Table 2-15). The estimated four year harvest for the fertilization treatment averaged 34,091 ODkg/ha at the Basher site and 29,506 ODkg/ha at the Morrison site. The control treatment at the Basher and Morrison sites had accumulated four year old biomass yields of 21,702 and 18,736 ODkg/ha, respectively. There were no significant site differences for the fertilization or control treatments in the total tree yields. The four year old 1981 planted fertilization trees growing at the Basher site had accumulated 40,488 ODkg/ha which was not significantly greater than the 37,454 ODkg/ha yields for the fertilization trees growing at the Morrison site (Table 2-15). The four year old yield for the 1981 planted trees growing at the Basher site was significantly greater than the control yield value (34,314 ODkg/ha) but the difference between the control and fertilization trees growing at the Morrison site was not significant.

Fertilization/Irrigation Effects - Fertilization/irrigation treatments consistently produced trees that were taller and larger in diameter than all other treatments. These larger trees also accumulated greater amounts of total OD biomass above a 15 cm stump than all other treatments. The only exception was the first growing season of the 1981 planted trees (Table 2-12).

In the second growing season the fertilization/irrigation treatments to the 1980 planted trees produced 6,792 ODkg/ha at the Basher site and 7,321 ODkg/ha at the Morrison site (Table 2-13). These accumulated total biomass values were significantly greater than all other treatments. For the 1981 plantings, fertilization/irrigation treatment units at the Basher site had accumulated 13,373 ODkg/ha which was significantly greater than the control

and irrigation treatment units but not the fertilization treatment unit (Table 2-13). At the Morrison site, the accumulated total two year old biomass for the 1981 planted trees averaged 12,963 ODkg/ha and this value was not significantly greater than any of the other treatments (Table 2-13). Averaged over year of planting, the fertilization/irrigation treatment unit yields at the Basher site and Morrison site were significantly greater than all other site specific treatments, except the Basher fertilization/irrigation treatment yields were not significantly greater than the Basher fertilization values.

The three year old fertilization/irrigation treatments continued to out produce all other treatments. Total tree OD yields for the 1980 planted fertilization/irrigation treatment units at the Basher site and at the Morrison site were significantly greater than the control and irrigation treatments but not the fertilization treatments (Table 2-14). The accumulated three year old total tree biomass value for the 1980 planted Basher fertilization/irrigation treatments units (average of 22,102 ODkg/ha) was not significantly different from the Morrison fertilization/irrigation treatment (20,968 ODkg/ha). The fertilization/irrigation yields for the 1981 planted trees paralleled the 1980 planted trees, except there was no significant difference between the fertilization/irrigation and irrigation yields at the Morrison site. The accumulated total tree OD biomass of 27,484 ODkg/ha for Basher fertilization/irrigation units was not significantly different from the 28,821 ODkg/ha of biomass accumulated by the same treatment Morrison trees.

At first rotation harvest age of four years, the fertilization/irrigation treatments for the 1980 planted trees produced the greatest amount of OD biomass above a 15 cm stump. Total tree yield of 35,901 ODkg/ha for the Basher fertilization/irrigation treatments was significantly greater than the control treatment only. At the Morrison site, the fertilization/irrigation treatments yielded 36,915 ODkg/ha and this value was significantly greater than the control and irrigation but not significantly greater than fertilization. There was no significant site difference in the 1980 planted four year old total tree yields for the fertilization/irrigation treatment units.

Fertilization/irrigation treatments to the 1981 planted trees also resulted in trees which produced the greatest OD first rotation potential yields. There was no significant difference between the four year old fertilization/irrigation total OD biomass yields of 42,612 and 44,685 ODkg/ha measured at the Basher and Morrison sites, respectively (Table 2-15). At each site, the fertilization/irrigation treatment units yield values were significantly greater than the control or irrigation treatment values. As compared to the fertilization treatments, the higher average fertilization/irrigation total oven OD yield for the 1981 planted units was not significant at the Basher site but was significant at the Morrison site.

Adjusted Yields - The total tree field weight yields and OD mainstem wood, mainstem bark, branch and leaf yields are presented in Tables 2-12, 13, 14 and 15. These yield values were predicted from the equations presented in Tables 2-7 to 11. At harvest, the field weight values for all living continuous inventory trees were determined from actual measurements. The

actual and equation predicted values for the 1980 and 1981 planted trees are presented in Table 2-16. The predicted values were reasonably close to the actual values for most site-treatment-year of planting combinations. These differences between the actual value and the predicted value were used to adjust the four year old OD mainstem wood, mainstem bark and branch material in Table 2-15. The adjusted four year old accumulated yields, by component, for each treatment at each plantation site and year of establishment are presented in Table 2-17. The adjusted yield values will be combined with the energy and chemical properties to provide inputs to the financial and energy analyses.

Nutrients - To estimate the potential soil nutrient drain from intensive culture of dense plantations, the nutrient levels in the Ap and upper 15 cm of the B soil horizons were measured annually (Appendix B, Tables B-1, 2). These analyses failed to suggest any negative changes in the soil nutrient levels over the first rotation. Most estimates of soil fertility increased over the four years of the first rotation, as compared to preplanting levels, for all treatment units (Appendix B, Tables B-1, 2). One possible explanation for these positive changes in soil fertility levels is the decomposition and incorporation of litter fall. The concentrations of macronutrients in the foliage and returned to the soil as fresh litter, and concentrations of these nutrients in the spring and late summer litter are presented in Appendix B (Tables B-20 to 27).

The concentrations of N, P, K, Ca and Mg in one, two, three and four year old biomass are presented in Appendix B (Table B-17 to 20). Estimates of the amounts of N, P, K, Ca and Mg contained in the four year old biomass removed in a first rotation harvest are presented in Tables 2-18 to 2-20. These nutrient values for mainstem wood, mainstem bark and total tree components are presented by year of establishment, plantation site and treatment. As expected, the macronutrient amounts in the biomass were greater for the fertilized treatment units than the non-fertilized treatment units. For all components of the biomass, the amounts of N, K and Ca accumulated were much greater than the amounts of P and Mg. Removal of N, K and Ca in the ranges presented in Tables 2-18 to 2-20 could reduce future production, if these nutrients were not replaced.

It appears from these soil fertility and nutrient uptake comparisons that: (1) either the soil testing procedures are not sufficiently sensitive to accurately measure the soil fertility changes or (2) the supply capacity of the soil plus the decomposition and mineralization of litter fall exceed the nutrient uptake of the trees in the first rotation.

Corn Plot Summary

To verify the effectiveness of the fertilizer program in achieving the desired soil nutrient status, six replicated (three started in 1980 and three in 1981, at each site) *Maize* Pioneer hybrid 3591 plots of standard research size (7.3 x 10 m) with 0.18 m between the rows and a projected surviving population of about 60,000 plants/ha were established adjacent to the tree plantings.

These 12 replicated 73 m^2 corn plots (6 at each site) were established adjacent to the *Populus* plots. Except for the 1983 growing season, annual

Table 2-16. Four year old field weight values from actual measurements and from equations presented in Table 2-10. These values are summations of all surviving individual tree weights per plot for the three 1980 planted replications and three 1981 planted replications per site.

Plantation Site Treatment	Field Weight Actual	Field Weight Predicted	Conversion Factor[1/]
	- - - tonne per hectare - - -		
1980 Planting			
Basher			
Control	45.77	44.23	1.03
Irrigation	65.10	65.35	1.00
Fertilization	70.21	70.70	.99
Fertilization/ Irrigation	77.39	75.76	1.02
Morrison			
Control	41.45	38.19	1.09
Irrigation	46.56	44.58	1.04
Fertilization	67.36	61.19	1.10
Fertilization/ Irrigation	78.99	77.90	1.01
1981 Planting			
Basher			
Control	71.96	69.94	1.03
Irrigation	67.90	63.90	1.06
Fertilization	87.85	83.96	1.05
Fertilization/ Irrigation	90.44	89.92	1.01
Morrison			
Control	64.42	65.03	.99
Irrigation	70.49	77.41	.91
Fertilization	79.56	77.67	1.02
Fertilization/ Irrigation	86.38	94.30	.92

1/Multiply predicted field weight value by conversion factor to obtain actual field weight.

Table 2-17. Actual four year total tree field weight (green) and adjusted oven dry weight, and oven dry mainstem wood, bark and branches at the end of the growing season. The adjusted values were calculated from the difference between actual and predicted values presented in Table 2-18.

Plantation Site	Treatment	Total Tree Actual Field	Adjusted Oven Dry Total Tree	Adjusted Oven Dry Mainstem Wood	Adjusted Oven Dry Mainstem Bark	Adjusted Oven Dry Branches
		tonne/ha				
1980 Planting						
Basher	Control	45.77	22.35	14.93	3.94	4.49
	Irrigation	65.10	31.50	21.93	5.06	5.85
	Fertilization	70.21	33.75	23.93	5.88	5.64
	Fertilization/Irrigation	77.39	36.62	26.35	5.83	5.71
Morrison	Control	41.45	20.42	13.64	4.00	4.10
	Irrigation	46.56	22.35	15.56	3.97	4.15
	Fertilization	67.36	32.46	23.01	6.05	5.43
	Fertilization/Irrigation	78.99	37.28	26.83	6.03	5.81
1981 Planting						
Basher	Control	71.96	35.34	23.61	5.83	7.10
	Irrigation	67.90	32.65	22.73	5.76	6.07
	Fertilization	87.85	42.51	30.14	7.20	7.11
	Fertilization/Irrigation	90.44	43.04	30.97	6.86	6.71
Morrison	Control	64.42	31.59	21.10	5.49	6.34
	Irrigation	70.49	33.95	23.64	5.46	6.31
	Fertilization	79.56	38.20	27.09	6.75	6.39
	Fertilization/Irrigation	86.38	41.11	29.59	6.45	6.41

Table 2-18. Estimated amount[1/] of N, P, K, Ca and Mg contained in the four year old mainstem wood, by year of planting, plantation site and treatment.

Plantation Site Treatment	N	P	K	Ca	Mg
	- - - - - - - - - - - - - -		kg/ha	- - - - - - - - - - - - - -	
1980 Planting					
Basher					
Control	18	5	15	19	3
Irrigation	26	7	24	29	5
Fertilization	40	7	29	31	5
Fertilization/ Irrigation	42	8	32	34	5
Morrison					
Control	19	3	11	18	4
Irrigation	20	3	12	19	5
Fertilization	41	5	18	28	7
Fertilization/ Irrigation	43	5	21	32	8
1981 Planting					
Basher					
Control	28	7	23	31	5
Irrigation	32	7	25	30	5
Fertilization	51	9	36	39	6
Fertilization/ Irrigation	49	9	37	40	6
Morrison					
Control	30	4	17	27	6
Irrigation	30	5	19	28	7
Fertilization	49	5	22	33	8
Fertilization/ Irrigation	42	5	21	32	8

[1/] Based on the adjusted oven dry weight of mainstem wood in Table 2-17 and the nutrient concentrations in the four year old wood (Appendix B, B-17).

Table 2-19. Estimated amount[1/] of N, P, K, Ca and Mg contained in the four year old mainstem bark, by year of planting, plantation site and treatment.

Plantation Site Treatment	N	P	K	Ca	Mg
	- - - - - - - - - - - - - -		kg/ha-	- - - - - - - - - - - -	
1980 Planting					
Basher					
Control	33	4	28	65	4
Irrigation	45	5	35	72	5
Fertilization	65	5	43	101	6
Fertilization/ Irrigation	62	5	42	91	6
Morrison					
Control	35	4	28	53	6
Irrigation	27	3	28	63	6
Fertilization	68	5	46	106	8
Fertilization/ Irrigation	66	5	46	99	8
1981 Planting					
Basher					
Control	50	6	41	96	6
Irrigation	51	5	40	82	6
Fertilization	79	6	53	124	7
Fertilization/ Irrigation	73	6	49	107	8
Morrison					
Control	49	5	38	72	8
Irrigation	37	4	39	88	8
Fertilization	76	6	51	119	9
Fertilization/ Irrigation	71	6	50	106	9

[1/] Based on the adjusted oven dry weight of mainstem bark in Table 2-17 and nutrient concentrations in the four year old mainstem bark (Appendix B, Table B-18).

Table 2-20. Estimated amount[1/] of N, P, K, Ca and Mg contained in the four year old total tree biomass (excluding leaves), by year of planting, plantation site and treatment.

Plantation Site Treatment	N	P	K	Ca	Mg
	- - - - - - - - - - - -		kg/ha-	- - - - - - - - - -	
1980 Planting					
Basher					
Control	64	11	65	98	11
Irrigation	98	14	98	137	16
Fertilization	125	14	98	151	17
Fertilization/ Irrigation	143	15	114	139	18
Morrison					
Control	53	8	53	82	10
Irrigation	54	7	60	96	11
Fertilization	120	13	94	162	16
Fertilization/ Irrigation	116	11	97	160	19
1981 Planting					
Basher					
Control	102	18	102	155	18
Irrigation	91	13	91	127	16
Fertilization	141	15	111	172	19
Fertilization/ Irrigation	160	16	127	156	21
Morrison					
Control	82	13	82	126	16
Irrigation	81	10	92	146	17
Fertilization	141	15	111	191	19
Fertilization/ Irrigation	127	12	107	177	21

[1/] Based on the adjusted oven dry weight of mainstem wood, mainstem bark and branches in Table 2-17 and nutrient concentrations in the four year old mainstem wood, mainstem bark and branches (Appendix B, Tables B-17, 18, 19).

total above average ground OD biomass production for these corn plots ranged from 11.81 ODt/ha to 24.25 ODt/ha and averaged 16.89 ODt/ha (Table 2-21). The 1983 growing season was a poor year for corn and the biomass ranged from 4.48 to 8.28 ODt/ha (Table 2-21). Including the 1983 production values, average annual production from first tilled to third no-till corn crops would have been 14.33 ODt/ha. Since these plots were fertilized by the same program as the fertilization Populus plots, the corn yields should be compared to the fertilization treatment unit yields. All fertilized Populus treatment units averaged 0.60 ODt/ha in the establishment year. In the second year, biomass production was 8.20 ODt/ha for an average annual production of 4.40 ODt/ha at the end of two growing seasons. The fertilized Populus treatment units produced 14.48 ODt/ha in their third growing season and average annual biomass production increased to 7.76 ODt/ha at the end of three years.

In the final year of the first rotation, all four year old fertilized trees produced 12.10 ODt/ha of total tree biomass. Averaged over the four years, the fertilized trees at the Basher and Morrison sites had an annual production of 8.85 ODt/ha of total tree biomass.

Since corn harvest included leaf material the comparison between corn and tree production values should include Populus leaves. Total Populus biomass production for the fertilized trees, including leaf value, for a given year, was 1.00, 10.98, 18.47 and 15.46 ODt/ha in the first, second, third and fourth growing seasons, respectively. Average annual production of total tree biomass for the fertilized trees, including all cumulative leaf production, was 1.00, 5.99, 9.95 and 11.33 ODt/ha after one, two, three and four growing seasons, respectively.

The corn plots were sampled according to standard agronomic methods, and nutrient contents in the selected components have been assembled (Table 2-22). Over four years of production, it is estimated that about 767, 120, 402, 104 and 99 kg/ha of N, P, K, Ca and Mg, respectively, would be removed in the stover and grain harvested from the Basher site (Table 2-22). It is estimated that a similar corn harvest at the Morrison site would remove 709, 109, 405, 136 and 104 kg/ha of N, P, K, Ca and Mg, respectively, (Table 2-22). Compared to the potential nutrient removal in total tree (excluding leaves) harvest of four year old Populus (Table 2-20), corn production would remove greater amounts of N, P, K and Mg and slightly lower amounts of Ca.

Herbaceous Plot Summary

Adjacent to the Populus study plots, twelve replicated (six at each site) 25.0 m^2 native herbaceous vegetation plots were maintained. Oven dry above ground annual herbaceous vegetation at the end of the growing season for grass (and grasslike), broadleaf weeds and total material one, two, three and four years after tillage is presented in Table 2-23. Total herbage increased with years after tillage. The Basher site herbaceous material ranged from 2.80 to 4.67 ODt/ha and annually averaged 3.48 ODt/ha. The Morrison site herbaceous material ranged from 1.90 to 3.53 ODt/ha and annually averaged 3.02 ODt/ha. Comparisons of data from the herbaceous plots should only be made with the Populus control plots. Total tree, excluding leaves, biomass for all one year old control trees averaged 0.60 ODt/ha. The two year old trees average production in the second growing

Table 2-21. Average[1/] field weight[2/] and oven dry weights[3/] of corn stover, ear[4/] and total plant for first tilled soil in 1980 and 1981, and no-tilled soil in 1981 and 1982. All plots were fertilized to yield 47 tonne of corn silage[5/] (field weight) per hectare.

Tillage-Year Site	Field Weight[2/]			Oven Dry[3/]			
	Stover	Ear[4/]	Total	Stover	Grain[6/]	Cob[7/]	Total
First Tilled				ODt/ha			
1980 Basher	12.20	11.01	23.21	5.00	4.81	2.00	11.81
Morrison	12.23	10.55	22.78	4.73	5.31	2.60	12.10
1981 Basher	15.63	16.86	32.49	6.61	8.68	3.13	18.42
Morrison	10.40	14.34	24.74	4.55	9.02	2.78	16.35
First No Till							
1981 Basher	15.79	16.15	31.95	6.63	8.38	3.07	18.08
Morrison	8.86	13.17	22.03	4.40	8.33	2.61	15.34
1982 Basher	17.55	10.11	27.66	5.98	4.88	2.22	13.08
Morrison	14.20	16.84	31.04	5.82	8.81	3.00	17.63
Second No Till							
1982 Basher	24.40	13.42	37.82	8.30	6.48	3.03	17.81
Morrison	13.50	16.39	29.89	5.53	8.57	2.89	16.99
1983 Basher	9.37	6.66	16.03	2.68	3.59	.52	6.79
Morrison	7.57	7.51	15.08	3.52	4.09	.67	8.28
Third No Till							
1983 Basher	13.82	1.26	15.08	3.66	.70	.12	4.48
Morrison	8.90	2.71	11.61	5.34	1.45	.21	7.00
1984 Basher	20.07	16.50	36.57	4.36	13.70	2.81	20.87
Morrison	29.10	15.96	45.06	8.31	13.90	2.04	24.25

1/ Average of three replicates/tillage/year/site.

2/ Measured in October two weeks after killing frost.

3/ Oven dry at 74°C until weight stabilized.

4/ Husked, grain on the cob.

5/ 47 tonne of corn silage at field weight with desired harvest moisture at 64% (wet weight basis) would equal about 17 oven dry tonne/hectare.

6/ Shelled grain weight yields for market values would be increased by 15.5% over oven dry value.

7/ Estimate by multiplying oven dry stover + grain values by 0.205 for First Tilled, First No Till, Second No Till (1982). Determined from measurements for all others.

Table 2-22. Average concentrations and estimated[1/] nutrient uptake[2/] values for mature stover and grain of associated corn plots from first tilled through third no-tilled soil.

Site Specimen	N	P	K	Ca	Mg
Concentrations	- - - - - - - - - -		% of OD wt.	- - - - - - - - - -	
Basher					
Stover	0.90	0.12	1.05	0.33	0.22
Grain	1.55	0.33	0.34	0.02	0.13
Morrison					
Stover	.76	0.09	1.07	0.44	0.23
Grain	1.63	0.28	0.30	0.02	0.12
Four Year Uptake	- - - - - - - - - -		kg/ha	- - - - - - - - - -	
Basher					
Stover	270	36	315	99	66
Grain	397	84	87	5	33
Total	767	120	402	104	99
Morrison					
Stover	224	26	316	130	68
Grain	485	83	89	6	36
Total	709	109	405	136	104

[1/] Average of six plots per site and four years of production.

[2/] Calculated from site-specimen specific yields (Table 2-21) and nutrient concentrations (above).

Table 2-23. Average[1/] oven dry weights of grass (and grasslike), broadleaf weeds and total herbaceous vegetation[2/] at the end of the growing season (September) on native vegetation plots that were adjacent to each plantation site. The 25.0 m^2 permanent plots were not fertilized or irrigated and replicated 6 times.

Plantation Site	Grass	Broadleaf Weeds	Total
	- - - - - - - -	tonne/ha	- - - - - - - -
One growing season after tillage			
Basher	.45a	2.35a	2.80a
Morrison	.12b	1.78b	1.90b
Average	.29	2.06	2.35
Two growing seasons after tillage			
Basher	.79a	2.31a	3.10a
Morrison	.15b	3.11b	3.26a
Average	.47	2.71	3.18
Three growing seasons after tillage			
Basher	.92a	2.41a	3.33a
Morrison	.48b	3.05b	3.53a
Average	.70	2.73	3.43
Four growing seasons after tillage			
Basher	.98a	3.69a	4.67a
Morrison	.40b	2.83b	3.23b
Average	.69	3.26	3.95

[1/] Means of four 1.0 m^2 plots per 3 replications for the one growing season (1981) after tillage. The two, three and four growing seasons after tillage are based on 6 replications (N=24). Values with the same letter within season after tillage are not significantly different at the 0.05 level.

[2/] See Appendix A (Table A-1) for list of species.

season was 4.65 ODt/ha or an average annual accumulated production of 2.63 ODt/ha. The three year old trees produced 9.21 ODt/ha of total oven dry biomass in the third growing season, and had an average annual accumulated production of 4.82 ODt/ha. In the last growing season of the first rotation, the control treatments produced 12.17 ODt/ha, and had an average annual accumulated oven dry production of 6.66 ODt/ha.

Since harvest of herbaceous vegetation includes leaf material, a more precise comparison would be Populus above ground biomass, including leaves. Including leaves, the average total biomass production of the one year old control trees was 1.00 ODt/ha. In the second year, total biomass, including leaves, was 7.34 ODt/ha or an average annual production of 3.87 ODt/ha of total biomass including one and two year old leaf production. Production of total biomass, including leaves, in the third growing season was 11.99 ODt/ha and the average annual production of total biomass, including one, two and three year old leaves, was 6.58 ODt/ha. In the final year of the first rotation for the 1980 plantings, the control treatment units produced 15.11 ODt/ha of total biomass, including leaves. Averaged over the four year rotation, these 1980 planted trees annually produced 8.71 ODt/ha of total tree biomass, including leaves from one, two, three and four years.

Production Summary

Total tree OD yields of the Populus hybrid trees planted on the two study sites indicate:

1. Proper weed control substantially increased biomass yields.

2. Biomass productivity was greater in the second year than the first year, greater in the third year than the second year and similar in the third and fourth years.

3. Favorable sites yielded slightly more biomass, in the same time frame, compared to unfavorable sites.

4. Irrigation, fertilization and fertilization/irrigation increased two, three and four year old biomass production.

At these study sites, biomass production rates from the Populus system appeared to be greater than a native herbaceous system but lower than the amount obtained from a corn production system. The trees have been slow to reach site occupancy and biomass production rates have been low in the first and second growing seasons. In the third and fourth years, the amounts of biomass produced by the Populus trees were similar to the average corn production rates.

The four year tree biomass production did not equal the targeted four year total corn production of 63 ODt/ha of biomass. The actual corn production also did not achieve the targeted production level. Low tree biomass production rates were expected for the first year. Higher biomass production rates were measured in the second, third and fourth years. At a density of one tree per 0.48 m^2, near maximum first rotation biomass production rates may be achieved in the third or fourth growing seasons for

some treatments, depending on weed control in the establishment year. The first rotation average total biomass yields (mainstem wood, mainstem bark and branch material) for the 1980 and 1981 plantings are presented in Figure 9. These one through four year old accumulated yield values for each treatment are averaged over plantation site.

At the end of the first rotation, the treatment dependent range in average total tree biomass yield was considerable for the trees planted in 1980 and substantial for the 1981 planted trees (Figure 9). The control trees with poor weed control in the establishment year (1980) averaged about 20 ODt/ha of total tree biomass at age four. Irrigation increased the accumulated four year old yields to about 27 ODt/ha, and fertilization produced about 32 ODt/ha at the end of the first rotation. The combined fertilization/irrigation amendments to the Populus trees planted in 1980 resulted in about 36 ODt/ha of total tree biomass at age four. Good weed control in the establishment year (1981) resulted in the control treatment producing about 33 ODt/ha of total tree biomass in the first rotation. Irrigation increased the four year old accumulated yields to about 34 ODt/ha and fertilization increased the yield to about 39 ODt/ha. Fertilization/irrigation to the trees established with good weed control resulted in first rotation yields of about 44 ODt/ha.

Over both sites and the two years of planting, the four year ranges in accumulated total biomass above a 15 cm stump for individual replications were extreme for control (9 to 35 ODt/ha), high for irrigation (21 to 40 oven dry tonne/ha) and fertilization (26 to 44 ODt/ha) and moderate for the fertilization/irrigation (35 to 47 ODt/ha).

Physical and Chemical Properties

Selected physical and chemical properties, related to the use of Populus hybrids as a source of fuel or chemicals, were analyzed for variations associated with the different cultural strategies within and between sites. Data included: 1) specific gravity (maximum moisture content method), 1) moisture content (ASTM D-2016), 3) gross heat of combustion (ASTM D-2015), 4) ash content (ASTM D-1102), 5) extractive content (ASTM D-1105), 6) holocellulose (acid chlorite method), 7) alpha-cellulose (ASTM D-1103) and 8) Klason lignin (ASTM D-1106).

Four year old wood, bark and wood/bark composite specimen values are summarized in Table 2-24. A complete set of the physical and chemical property data by management strategy, site, age and tissue component are given in Appendix B (Tables B-28 through B-35).

Moisture content of four year old material averaged 97%, 102% and 108% for wood, wood/bark composite and bark, respectively. Wood moisture content decreased with increasing age and bark moisture content increased with increasing age. While moisture content was statistically insensitive to management strategy, it did vary with site.

Specific gravity was largely insensitive to any management strategy or site effects. Four year old wood, wood/bark composite and bark specific gravity values were 0.385, 0.387 and 0.339, respectively. Wood density decreased with increasing age, with the largest change occurring between ages two and three, a period of rapid growth. No such trend was evident for bark.

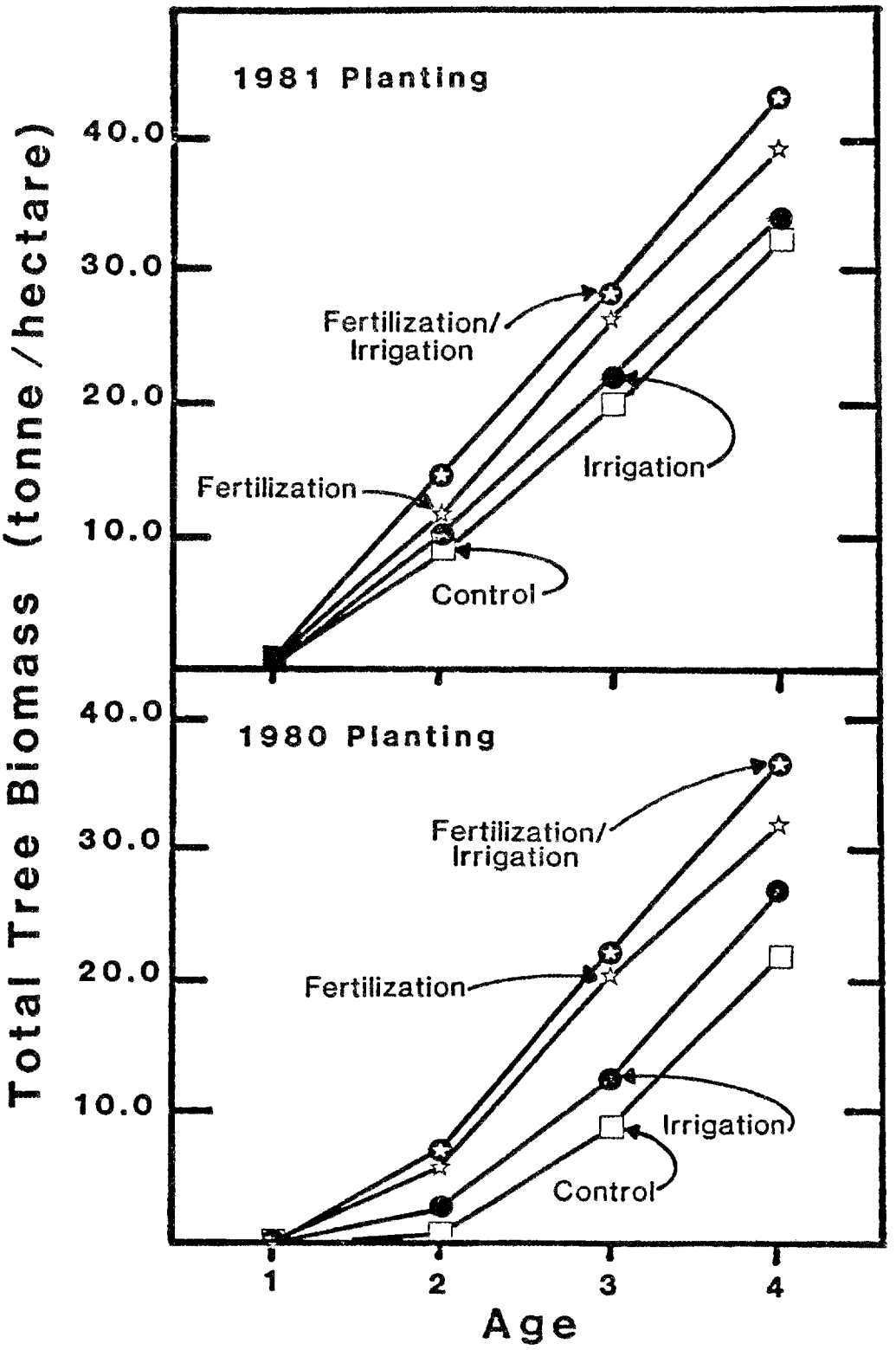

Figure 9. Average total biomass (mainstem wood, mainstem bark and branch material) for 1980 and 1981 plantings for one through four years of the first rotation, averaged over plantation sites.

Table 2-24. Selected physical and chemical properties of four year old Populus hybrids.[1/]

Component	Management Strategy	Specific Gravity[2/]	Moisture Content[3/]	Gross Heat of Combustion[4/]	Ash[5/]	Extractive Content[6/]	Holo-cellulose Content[7/]	Klason Lignin Content[8/]	Alpha Cellulose Content[9/]
Wood	Control	0.389	99.2	4621	0.43	5.62	83.89	16.32	46.60
	Fertilization	0.368	98.0	4590	0.51	5.36	82.78	16.47	46.68
	Irrigation	0.402	96.6	4628	0.47	5.39	84.05	15.94	46.53
	Fertilization/ Irrigation	0.381	97.3	4579	0.48	5.24	82.82	15.26	46.23
Wood/ Bark	Control	0.387	101.2	4647	1.05	11.54	74.45	16.62	45.99
	Fertilization	0.378	103.1	4650	1.20	10.87	75.73	17.30	46.51
	Irrigation	0.397	105.9	4651	1.18	10.70	76.66	16.97	46.18
	Fertilization/ Irrigation	0.388	102.2	4614	1.00	10.45	75.35	16.64	46.29
Bark	Control	0.332	106.8	4792	5.13	41.16	43.34	14.59	44.38
	Fertilization	0.338	111.2	4737	5.31	41.32	43.99	13.95	45.34
	Irrigation	0.341	106.2	4773	4.83	41.60	44.10	15.79	44.67
	Fertilization/ Irrigation	0.348	108.8	4720	5.16	41.59	43.93	14.39	44.76

1/ Specific gravity and moisture content values are based on an averge of 9 specimens per plantation establishment year per site. Gross heat of combustion, ash, holocellulose, Klason lignin and alpha cellulose values are based on an average of 3 specimens per plantation establishment year per site. Extractive content values are based on an average of 7 specimens per plantation establishment year per site.

2/ Maximum moisture content method, Smith, D. M. 1955. Maximum Moisture Content Method for Determining Specific Gravity of Small Wood Samples, USDA Forest Service, Forest Products Lab., No. 2014, 8 pp.

3/ ASTM D 2016, oven dry asis, %.

4/ ASTM D 2015-66, oven dry basis, cal/g.

5/ ASTM D 1102, oven dry basis, %.

6/ ASTM D 1105-56, oven dry basis, %.

7/ Acid chlorite method, Browning, B. L. 1967. Method of Wood Chemistry, Vol. II, Interscience Publishers, New York, oven dry basis, %.

8/ ASTM D 1103-60, oven dry extractive free basis, %.

9/ ASTM D 1106-56, oven dry basis, %.

Ash concentrations were substantially higher in one year old wood than two, three and four year old wood and were substantially lower in one year old bark than two, three and four year old bark. Four year old means were 0.5%, 1.1% and 5.1% for wood, wood/bark composite and bark, respectively. There were significant differences in ash content among management strategies and between sites.

Differences in gross heat of combustion values may be related to differences in extractive and lignin contents of the material. Gross heat of combustion values of four year old bark, 4755 cal/g, were higher than that of wood/bark composite, 4640 cal/g, and wood, 4604 cal/g. This may be associated with bark's high extractive content (41%) as compared with wood/bark composite (11%) and wood (5%). Extractive content of wood decreased with increasing age. Extractive contents of bark were relatively low in ages one and four, and were relatively high in ages two and three. Lignin content values of four year old wood, wood/bark composite and bark were 16%, 17% and 15%, respectively. While there were significant differences in gross heat of combustion, extractive content and lignin content values among management strategies and sites for some specimens, no consistent trends were evident.

Ethanol produced from woody biomass is converted from holocellulose and the ethanol yield primarily depends on cellulose concentrations of the woody biomass. Holocellulose content of wood and bark increased with increasing age. Four year old wood, wood/bark composite and bark values averaged 83%, 76% and 44%, respectively.

Alpha cellulose content of wood also increased with increasing age. On an OD extractive free basis, four year old wood, wood/bark composite and bark values were similar, averaging 46%, 46% and 42%, respectively. Converting these values to an OD basis, average alpha cellulose contents were 44%, 41% and 25% for wood, wood/bark composite and bark, respectively. Alpha cellulose and holocellulose values were largely insensitive to site; however, some treatment effects were evident.

Juvenile wood often exhibited different physical an chemical characteristics than older material. Therefore, while certain properties appear to vary with age, these trends usually become minimal in three and four year old material.

Most physical and chemical properties did not vary significantly with site at the 0.05 level except for ash and extractive content. There were statistically significant differences in properties among management strategies. However, these differences did not necessarily exhibit consistent trends and the magnitude of these differences within a property were generally quite small.

Economic Analysis Summary

The financial and energy maintenance costs for the first rotation are summarized in Table 2-25. The highest annual energy cost for maintaining the fertilization treatment unit was associated with ammonium nitrate. In contrast to the energy results, the highest annual financial cost was associated with ammonium nitrate on the Basher site and lime on the

Table 2-25. Summary of the financial and energy maintenance costs for the first rotation.

Maintenance	Basher Site		Morrison Site	
	10^6 kcal/ha	$/ha[1/]	10^6 kcal/ha	$/ha[1/]
Operations				
Insecticide/Fungicide	.944	70.70	.944	70.70
Property Rental and Tax	44.316	297.54	44.316	297.54
Management	.005	203.79	.005	203.79
	45.265	572.03	45.265	572.03
Cultural Amendments				
Fertilization	12.327	410.24	15.428	551.09
Irrigation	5.253	1754.67	5.516	2059.34
	17.580	2164.91	20.944	2610.43

[1/] Total cost for 4 year period, discounted at 5% annual.

Morrison site. The annual financial and energy costs for maintaining the fertilization treatment units were higher for the Morrison site than the Basher site.

The estimated irrigation financial and energy costs needed to maintain a commercial *Populus* hybrid plantation were (Tables 1-10 and 1-11) based on analyses of material requirements and costs given in Reed *et al.* (1976), Funk *et al.* (1980), Pimentel (1980) and from the experimental plantations. Based on these analyses, the annual financial and energy costs for establishing the irrigation system were lower than the annual maintenance and operation financial and energy costs.

A summary of the financial and energy costs for maintaining a commercial plantation (Table 2-25) listed the highest operation cost as property rental and tax. Financial costs for management were higher than insecticide/fungicide costs while the energy costs for insecticide/fungicide exceeded the costs for management. This was primarily due to management having a relatively high salary cost but a miniscule energy cost. Examination of the cultural amendment costs revealed that energy costs for fertilization were higher than irrigation while financial costs for irrigation were higher than fertilization. In addition, the costs for cultural amendments were higher at the Morrison site. These data were used as inputs to the LP model.

Task 3 - Analysis of Biomass Financial and Energy Data

The financial and energy analyses in this project were based on a self-owned, fully integrated commercial-scale operation. Costs for nursery stock, establishment and cultural maintenance operations were developed from field data obtained in this project, and combined with operational information in the literature supplemented by consultations with agricultural engineers and professional farm managers. These production costs were coupled with harvest, transportation, storage and conversion costs obtained from the literature for use in analyzing the self-owned commercial-scale operation from production through conversion.

The financial and energy model for this project balanced the inputs for producing, harvesting, transporting and processing against the recoverable outputs from the forest biomass. The LP basis for analyzing the biomass system characterized it as a production function and related inputs (e.g., fertilizer, irrigation amendments, etc.) to outputs (e.g., financial and energy gains). All of the facets of research within this project were entered into the problem as alternative strategies for growing biomass, harvesting the product and converting the material to energy. The solution to this problem represented a selection of the most efficient strategies for attaining a maximum net financial or maximum net energy output from the system.

Two of the key rationales for this research effort were to determine the actual yields from a set of alternate management strategies and to analyze these production efforts as full cost, self-owned, commercial-scale operations. Although previous studies have reported yields from intensive culture plantations, few of these have compared the efforts of alternate management strategies. Nor have these efforts evaluated their financial potential under the mandates of a commercial-scale operation.

The first portion of this project was the establishment and maintenance of an intensive culture plantation. The second portion compared the financial and energy costs of producing, harvesting and processing biomass against the recoverable output. Linear programming was used to analyze the various input requirements, associated constraints and outputs among the various management strategies and among the eventual combination of alternate management/harvest/conversion systems. Two objective functions were used in gaining alternate solutions to the model: maximizing net financial and net energy values. The overall LP design compartmentalized the functions into separate units. These units followed the sequential order: 1) biomass production, 2) harvesting, transportation, 3) storage and 4) conversion of biomass to energy. Sub-units, or strategies, were established within the various units as a means of ordering and analyzing alternative methods of production. Functionally, the model identified the "best route" among the complex of management/harvest/conversion alternatives and also permitted a sensitivity analysis of key variables within the model.

Short-rotation biomass plantations require many of the practices used for row crops. The research plantations, though much smaller in size than the proposed commercial systems, were functional in identifying the necessary field operations for each phase of work. Various agricultural engineering

standards were subsequently used to determine the probable operational characteristics, time constraints and financial and energy costs for self-owned commercial-sized plantations. The size was based on initial estimates of the output requirements from the total system.

The financial analysis literature review centered on the economics of producing intensively managed, short-rotation Populus hybrid plantations, with particular attention directed to the costs of site preparation and establishment. However, cost estimates may change due to inflationary trends, improving technologies, location and site qualities. In the final analysis, the real merit of these previous studies was in their methodology for evaluating the production function.

Limited information was available on formal research of biomass production systems. However, certain cost estimates were drawn from the conceptual models depicting various aspects of the agricultural and forest sectors. The intensity of the proposed biomass systems was similar to agricultural production and in several cases similar machinery was proposed. Comparative cost estimates for site preparation and establishment of short-rotation plantations were provided by DeBell and Harms (1976), Inman et al. (1977), Mace and Gregersen (1975).

Biomass Financial and Energy Input Accounting

All production operations were cost analyzed on the basis of financial and energy expenses. In the financial and energy conventions, costs were divided into variable and fixed expenses associated with the self-ownership of all capital equipment.

Financial Accounts - Total financial costs were compared to agricultural contract rates to check the relative accuracy of the accounting methods and to evaluate the merits of self-ownership. In all cases the estimates were sound and confirmed the logic of self-ownership under the proposed scale of operations.

All of the financial values for plantation establishment and maintenance were for the base year 1981. Capital costs were prorated over their expected operational lifetime and also incorporated a 5% annual real interest charge on their nondepreciated value. The initial costs of plantation establishment were prorated over their expected 20 years lifetime in a similar fashion. When the financial analysis required a development of present discounted values, all future values were discounted at the 5% annual real interest charge. In a reciprocal fashion, the compound future costs at the conclusion of the first rotation were based on a 5% annual rate of interest charge. This rate represented a compromise between the 6% historic and projected after-tax real rate on U.S. corporate capital reported by Klemperer (1979) and the 4% real rate proposed by Row et al. (1981) as the current marginal long-term expectations on new productive investments.

Variable costs for an operation included labor, fuel, materials and maintenance of the equipment. Base pay rates were taken from Doane's (1981) with 5 to 20% added for fringe benefits. Fixed costs included insurance, equipment shelter, depreciation and interest. Annual insurance

and shelter charges were 1.5% of the equipment's original list price. Depreciation and interest were treated as an annuity payment to reflect the recovery of the original net investment and an interest charge on the remaining principal.

For cost accounting purposes plantation production was divided into: (1) establishment, (2) maintenance and (3) the cultural amendments of fertilization and irrigation. Establishment included herbicide, mower-conditioner and offset disking operations during the fall season followed by the spring operations of disc harrowing, pre-emergence herbiciding and planting.

Each establishment operation was sequentially analyzed in terms of: (1) the areal rate of production for the central unit of equipment, (2) the power and allied fuel requirements of the unit, (3) the volume of land prepared per equipment unit during the limits of the annual time frame and (4) the number of equipment units required for the proposed size of operations. The offset disking operation was the critical constraint to the volume of land prepared during the establishment phase. The central unit, a 170 hp tractor, can prepare an area of 924 ha during the 11 week fall plowing period available to our region. By establishing the base working unit at 924 ha, all other establishment operations would be completed within their respective time frames.

The largest cost in the establishment phase was for the hybrid poplar cuttings. With an annual requirement of 20 million cuttings (21,000/ha) the least cost approach in developing this supply was to operate a satellite nursery. Nursery operations were based on the same fertilization/irrigation management strategy proposed for the plantations. An estimated annual yield of 350,000 cuttings/ha would be produced from the nursery after an initial two year establishment period.

Costs of cuttings were developed on the assumption that they would be produced in the production/conversion facility's self-owned and operated nursery. These actual costs for cuttings will probably be lower than cutting costs for an operation which purchases cuttings from an independent profit oriented nursery.

Maintenance costs included biennial pesticide and fungicide treatments, land rent, land taxes and overhead management. A helicopter spray system was used in the application of insecticides and fungicides during the third year of the rotation. The total costs of self-owned helicopter spray systems were compared to the costing and mark up procedures employed by contract helicopter spray services. This verified the cost advantage of self-owned equipment over contract services when the equipment was employed over 50% of its expected operational capacity.

Land rent represented the opportunity cost of using these types of land for biomass production. The most likely alternative use for the Basher and Morrison sites was in corn production. As such, the rent payment was the net revenue earning capacity of land from corn production. The net return from corn production was the difference between the gross revenue earnings from this output and the sum of the production and drying costs, property taxes and federal income taxes. An analogous study was made of the net energy gain secured from corn production (Appendix C, Table C-1).

Dum et al. (1977) estimated 272 bu/ha as the probable output from a "good" corn production site such as found on the project's plantations. Gross revenue was based on a 5-year average farm price net of hauling and marketing costs (Pa. Dept. of Agric. 1982). This average price of $2.87/bu resulted in a gross return of $781.18/ha. Production costs were based on 1980 Pennsylvania estimates for producing 120 bu of corn per acre (Pa. Dept. of Agric. 1982). This cost ($601.19/ha), adjusted to the base year (1981), also included a managerial charge of 5% of gross revenues per hectare. Drying costs were included as a necessary cost for marketing the output at a $2.87/bu price. A custom rate for drying of $.26/bu was used in establishing the costs per bushel (King 1981).

The property tax was assessed in a manner consistent with comparable agricultural lands. It was based on the preferential assessment procedures available under Pennsylvania's Act 319 statutes. Tillable land in Centre County, Pennsylvania, has been valued at $370.65/ha over the last few years (Centre County Real Estate Assess. Off., 1982, 1983). Using an assessment ratio of 20% and an average real estate millage rate of 100.94 mills per $1.00 of assessed value (or $.10094/1.00) for 37 districts in Centre County, Pennsylvania, the estimated property tax on agricultural property was: $370.65/ha x 0.2 x $.10094 = $7.48/ha. Since this estimated tax was for 1980, its value was compounded forward at a 5% rate for one year, yielding a final value of $7.85/ha. The federal income tax was based on an average tax rate of 25% as applied to all net revenue, after payment of property tax.

The results of this financial analysis indicated that land's annual net return from corn production would be $76.06/ha (Appendix C, Table C-1). Using this return as a constant annual perpetual series, the present net worth of the property would be $1521.20/ha, when using a 5% rate of discount.

Gingrich and Shortle (1984) provided a comparative study of agricultural land values in Pennsylvania for the period 1976-81. Their data base was drawn from farm transfers financed through the Federal Land Bank (FLB). This particular agency financed an average of 32% of all credit-financed farm real estate sales in the Northeast for the years 1975-82. The land value for farm real estate in the central Pennsylvania region during their study period averaged $1856/ha. Further stratifications of their data base indicated selling prices of land used for field crops averaged at $1935/ha. Comparisons of the FLB data with similar types obtained by the USDA Economic Research Service and by the U.S. Department of Commerce indicated FLB data to be 25% to 35% higher than the other two sources.

Although this project's estimated land value of $1521/ha was lower than the FLB market prices it did fall within the range of the market prices presented by all three sources. These market prices may not necessarily be guided by the financial principles used within this project, but the results are comparable and, as such, do support the land rent charge used within this project.

The managerial requirements for planning, implementing and supervising a commercial biomass plantation, as proposed in the LP model, were developed from estimates based on the project's field experience and allied input

requirements. Also examined were certain managerial parameters and conceptual plantation designs suggested by Inman et al. (1977).

The breakdown of management responsibilities for the staff was based upon the needs of a commercial forest enterprise. A head supervisor would be in charge of the total operation and be assisted by a head clerk and an assistant clerk. Under the supervisor, a field manager and a clerical assistant were charged with running all on-site operations. A network of foremen, responsible to the field manager, would take charge of important operational phases of the plantation.

In the LP model, it was assumed a managerial and supervisory staff of 10 people would oversee four working units (3696 ha). At the onset, one 924 ha working unit was established each year. After four years and each year following, a working unit would be coppiced followed by subsequent regrowth. The managerial structure for this commercial plantation system involved a total annual salary cost of $212,400 or $57.47/ha/yr (Appendix C, Table C-2).

For fertilization strategies, the plantation's four year regimen of phosphate and potash would be applied by tractor during the first year's establishment phase. Also the plantation's four year lime needs would be applied during this onset. The first year's nitrogen needs would be applied by tractor during the establishment phase with the subsequent annual applications made by helicopter.

The cost analysis of the commercial trickle irrigation systems included establishment costs for both well and free-flowing stream water sources and the expected operating and maintenance costs of the trickle system. The capacities and rates of usage for both sources reflect the commercial operation of this overall strategy. These data are presented under Task 1 of this report and summarized in Tables 1-10 and 1-11.

Energy Accounts - The accounting convention for energy values was largely patterned from Pimentel (1980). In this approach, equipment energy was divided into: (1) energy embodied in the equipment's materials, (2) energy employed in the fabrication of the equipment and (3) energy embodied in repair parts. Each piece of equipment was itemized as to its weight in steel, rubber and other base materials, with these weights multiplied by their respective kilocalories of energy per kilogram (kcal/kg). Fabrication energy was the product of the kcal/kg of fabrication energy for particular types of equipment and the unit's total weight. Repair energy was the proportion of the unit replaced over its lifetime and was an appropriate fraction of the embodied and fabrication energies. The fixed hourly cost of operations was obtained by dividing the sum of the three energy sources by the equipment's wearout lifetime. This general procedure provided the fixed energy cost for all equipment used in establishment, maintenance and fertilization-irrigation.

The variable energy costs for materials such as fuel, herbicides, pesticides, fungicides and fertilizers were the products of their respective kcal/kg and amount used in their particular operation. The caloric expenditure of energy for human labor was itemized as a management cost but proved to be a rather small input, also confirming Pimentel's (1980) measure of this resource.

The energy equivalent for land rent was the net energy return from corn production foregone by the use of the site for biomass production. Pimentel (1980) used a measure of 3483.29 kcal/kg as the gross energy from corn grain. The energy input requirements for growing corn in southeastern Pennsylvania were 4.65 million kcal/ha for an output of 5,138.17 kg/ha (Pimentel 1980). Similar estimates verified this figure (F.E.A. 1976). The drying costs were based on fuel expenditures for corn drying (Wynn 1977) and machinery costs derived from a machinery/fuel ratio for agricultural production inputs. The energy equivalent for property tax was the energy/financial ratio for land rent ($.132 \times 10^6$ kcal/$1) multiplied by the financial cost of the tax. The net energy analysis for the research sites in the project compared favorably to the energy accounts constructed by Pimentel (1980) for several northeastern corn production centers.

An evaluation was made of the human energy expended by the management positions of the plantation operation. Overall, these management and clerical functions entailed the greatest quantities of annual manpower in the biomass plantation system. The energy accounting method was adapted from Guthrie (1975). This involved a comparison of the average kcal expended per year for a management or staff position to the kcal expended by an inactive individual. The difference between levels represented the added net human energy expended by the management function. The costs (kcal/ha) used in the LP model were the total annual net energy expenditures divided by the total number of hectares under management (Appendix C, Table C-3). The low energy expenditure for management personnel (210 kcal/h) reinforced the rationale for not extending a similar analysis to the labor used in the establishment and maintenance operations.

Biomass Production Function

Control - Table 3-1 summarizes the total discounted costs for the various strategy/site options during the first rotation. Total control strategy costs for establishing and maintaining the plantations were identical for both sites ($834.73/ha). The greatest expense for the control strategy was land usage (rent and tax), with rent comprising nearly one third of the total cost. The second highest cost was management, amounting to 24% of the total. Planting costs were 23% of the total, with cuttings, via the nursery operation, contributing 85% to planting costs. The remaining major expense was the charge for insecticides and fungicides -- about 9% of the total. Overall, nearly 69% of the costs in the control strategy, rent, taxes, management and spray operations were fixed cost related.

Energy costs are summarized in Table 3-2. Land rent accounted for nearly 87% of the total energy costs. Although this energy was not actually used in biomass production, it was included as a minimal expected energy return for employing land in biomass rather than corn production.

Of the remaining 1.7 million kcal/ha of energy actually used in the control strategy, 56% was tied to the biennial insecticide and fungicide operation and 32% to the planting operation. The major energy input within the spraying operation was for materials, representing 82% of this operating cost.

Table 3-1. Financial summary of operational and strategy costs[1/] for first rotation Basher and Morrison site plantations.

	Basher Site	Morrison Site
	- - - - - - - - ($/ha)	- - - - - - - -
A. Operational Costs:		
1. Establishment		
Mower	2.65	2.65
Disc	4.77	4.77
Herbicide	59.84	59.84
Harrow	3.36	3.36
Plant	192.08	192.08
	262.70[2/]	262.70[2/]
2. Maintenance		
Insect./Fung.	70.70	70.70
Property Rental	269.70	269.70
Property Tax	27.84	27.84
Management	203.79	203.79
	572.03	572.03
3. Cultural Amendment		
Fertilization	410.24	551.09
Irrigation	1754.67	2059.34
	2164.91	2610.43
B. Total Strategy Costs:		
Control	834.73	834.73
Fertilization	1244.97	1385.82
Irrigation	2589.41	2894.08
Fert./Irrig.	2999.65	3445.17

[1/] Total cost for 4 year period, discounted at 5% annual.

[2/] The total establishment cost of $923.26/ha was prorated over 5 rotations (20 years), with the cost for the first rotation ($262.70/ha) representing the discounted sum of the first 4 years of annuity payments.

Table 3-2. Energy summary of operational and strategy costs for first rotation Basher and Morrison site plantations.

	Basher Site	Morrison Site
	- - - - - - (10^6 kcal/ha) - - - - - -	
A. Operational Costs:		
1. Establishment		
Mower	0.012	0.012
Disc	0.031	0.031
Herbicide	0.154	0.154
Harrow	0.014	0.014
Plant	0.525	0.525
	0.736[1/]	0.736[1/]
2. Maintenance		
Insect./Fung.	0.944	0.944
Property Rental	40.071	40.071
Property Tax	4.245	4.245
Management	0.005	0.005
	45.265	45.265
3. Cultural Amendment		
Fertilization	12.327	15.428
Irrigation	5.253	5.516
	17.580	20.944
B. Total Strategy Costs:		
Control	46.002	46.002
Fertilization	58.329	61.430
Irrigation	51.255	51.518
Fert./Irrig.	63.582	66.946

[1/] The total establishment cost of 3.68 x 10^6 kcal/ha was divided over 5 rotations, with the cost for any one rotation placed at .736 x 10^6 kcal/ha.

Fertilization - The fertilization strategy added 49% and 66% to the base cost of the control strategy on the Basher and Morrison sites, respectively. The less favorable Morrison soils cost 35% more for fertilization than the Basher soils.

Ninety-eight percent of the fertilization cost (12.3 x 10^6 kcal/ha and 15.4 x 10^6 kcal/ha for the Basher and Morrison sites, respectively) was for materials. Fertilization costs were from 7 to 9 times more expensive than the total of all other direct energy costs used in establishment and pesticides on the Basher and Morrison sites, respectively.

Irrigation - Irrigation more than tripled the financial costs of the control strategy on both sites. It cost more at the Morrison site ($2059/ha) than the Basher site ($1755/ha). Seventy-seven percent of the difference between sites was for the increased capital outlay of the well system, with the remaining 23% attributed to increased energy needs in pumping water at the Morrison site.

Irrigation also involved a heavy energy investment, with 5.2 million kcal/ha expended on the Basher site and 5.5 million kcal/ha on Morrison. Approximately 5% of this amount was for the annual energy cost of moving water to the trees, with the remaining 95% associated with equipment use.

Production Cost Summary - The total production costs at the conclusion of the first 4 year rotation ranged from $1,014.61/ha for the control strategy on both Basher and Morrison sites to $4,187.61/ha for the fertilization/irrigation strategy on the Morrison site (Table 3-3). All costs are reported as capitalized or end-of-the-rotation expenses.

The distribution of these strategy/site production costs over their respective biomass output depicts the relative competitiveness among these options (Table 3-3). For both sites, the control strategy was the least expensive followed by fertilization, fertilization/irrigation and irrigation in order of increasing cost. The least expensive strategy was the control option on the Basher site ($28.71/ODt) and on the Morrison site ($32.12/ODt). The increased production cost for fertilization was not matched by the output gain from fertilization at either site. This resulted in higher production costs per unit output for the fertilization strategies ($35.60/ODt on Basher and $44.10/ODt on Morrison). Fertilization output was 24% more expensive than control on the Basher site and 39% more expensive on the Morrison site. The poorer financial performance of the Morrison site was attributed to the greater cost of fertilizer materials for this nutrient-deficient site and a lower output caused by its drier aspect.

The addition of irrigation to either site caused a substantial increase in output costs. For irrigation on Basher costs were $96.40/ODt and on Morrison, $103.62/ODt. The addition of fertilizer to the irrigation strategy caused some reductions in production costs due to the increased output - from $96.40/ODt for irrigation/Basher to $84.71/ODt for fertilization/irrigation (a 12% reduction) and from $103.62/ODt for irrigation/Morrison to $101.86/ODt for fertilization/irrigation (a 2% reduction). In both instances the cost increase for fertilization was exceeded by its output increase. However, from a composite strategy view

Table 3-3. Financial and energy costs for production of first rotation yields.

Site	Management Strategy	Biomass Yield[1/] (ODt/ha)	Total First Rotation Production Costs[2/] $/ha	10^6 kcal/ha	$/ODt	10^6 kcal/ODt
Basher						
	Control	35.34	1,014.61	46.002	28.71	1.302
	Irrigation	32.65	3,147.43	51.255	96.40	1.570
	Fertilization	42.51	1,513.26	58.329	35.60	1.372
	Fertilization/ Irrigation	43.04	3,646.08	63.582	84.71	1.477
Morrison						
	Control	31.59	1,014.61	46.002	32.12	1.456
	Irrigation	33.95	3,517.76	51.518	103.62	1.517
	Fertilization	38.20	1,684.47	61.430	44.10	1.608
	Fertilization/ Irrigation	41.11	4,187.61	66.946	101.86	1.628

1/ Four year old adjusted OD total tree yield.

2/ Total costs of establishment, operations and maintenance, capitalized to the end of the first four year rotation at 5% rate.

the cost advantages from fertilization were overwhelmed by the cost requirements of irrigation. In short, although the margin from fertilization was attractive, the composite venture of fertilization/irrigation was prohibitive.

The energy costs per unit output for the first four year rotation resulted in the same approximate least cost positions among the strategy/site options as was evident in the financial critique (Table 3-3). However, the magnitude of difference among the options was far less than in the financial analysis and certain realignments in least cost priorities occurred. Within the Basher site, the least expensive strategy was control (1.302×10^6 kcal/ODt), followed by fertilization (1.372×10^6 kcal/ODt), fertilization/irrigation (1.477×10^6 kcal/ODt) and irrigation (1.570×10^6 kcal/ODt).

These followed the same positions as displayed under the financial analysis but with smaller relative differences between their values. For example, the increase in cost per unit of output between fertilization and fertilization/irrigation was 240% under the financial analysis but was only 8% in the energy analysis. On an energy measurement basis the fertilization/irrigation strategy used only 9% more energy than the fertilization strategy and developed a slight increase in output (1%). However, as previously referenced, the financial cost of the irrigation amendment was prohibitive to the overall economics of the latter strategy.

A different positioning of strategies was evident on the Morrison site. Control was still the least expensive at 1.456×10^6 kcal/ODt, followed now by irrigation (1.517×10^6 kcal/ODt), fertilization (1.608×10^6 kcal/ODt) and fertilization/irrigation (1.628×10^6 kcal/ODt). Irrigation of this drier site resulted in a positive output gain that was not evident on the Basher site. Furthermore, irrigation required a smaller energy increase than did fertilization. The net result was a lower energy input per unit output for irrigation on Morrison than was true for fertilization on Morrison. However, the financial cost of fertilization was far less than for irrigation.

Harvest and Storage Stages

The complete biomass supply system proposed and analyzed by this project incorporated production, harvest and transport, storage and final conversion to particular outputs. As such, a review of the technical and cost parameters within the ensuing stages of supply was necessary to determine the economic potential for any complete system.

Harvest Literature Review - The emergence of harvest technology for short rotation, closely spaced forest plantations has taken two allied approaches. First, traditional harvesting systems have been examined and modified (Cullen and Barr 1980; Sirois 1981; Stuart *et al*. 1981; Mattson 1983; McKenna 1984). Second, new prototype harvesting systems have been proposed and developed (Sirois 1982; Mattson 1983; Stuart *et al*. 1983a, b; Teel 1983). Marley (1982) outlined the essential phases in harvester research to include machine characteristics, severance methods, biomass collection/reduction and transport/storage considerations. McKenna (1984) stated that the key to an efficient operation was through the appropriate

scheduling of equipment in each phase. This achieves a smooth flow of operations, whereby no one phase hinders the productivity of another.

Cullen and Barr (1980) analyzed current forestry and agricultural harvesting systems. They concluded much of the existing technologies could be employed in harvesting woody biomass. However, certain obstacles, such as weather and terrain, might cause decreased production rates if standard technologies were applied to biomass systems. Marley (1982) supported the contention that new harvest technology will be a blend of existing equipment capabilities with the production needs of agricultural and forestry systems. Within the forest products industry most studies ruled out the traditional feller/buncher/skidder systems for the harvest of small diameter, closely spaced trees. The general limit to these systems was cutting one tree at a time, even though some accumulations of cut trees may occur before unloading (Sirois 1981). This lower productivity rate led to higher per unit costs, particularly when applied to small sized material. Mattson (1983) reported the cost of this traditional system increased as the spacing and size of trees decreased. Schiess (1984b) also concluded that the increase of trees per unit area and reduction of stem sizes accelerated harvesting costs on a per unit output basis. For closely spaced plantations it would be imperative to harvest on some continuous or multi-tree basis.

Sirois (1981) discussed the use of in-field chipping systems for smaller trees. While some chippers relied on the felling/bunching process, several units could swath harvest and chip simultaneously. In a subsequent article, Sirois (1982) considered the development and potential of the mobile chip harvester which could harvest and continuously chip small diameter trees. Schiess (1984b) found lower harvesting costs could be expected for systems having machines with continuous processing functions and well matched to tree dimensions.

Mattson (1983) reviewed worldwide harvest technologies adaptable to plantations of small diameter trees. One potential design was a USDA Forest Service prototype harvester with certain innovative engineering concepts. The tractor-pulled machine included a felling head, a directional felling device and an accumulator. Once evaluated, these concepts could be incorporated into the base design for commercial harvesters. Stuart et al. (1983a, b) developed and field tested a tractor-powered harvester that row harvested small diameter trees and then crushed their outer bark to facilitate field drying. This system can be complemented with a tree baler recovery system. In a previous study, Stuart et al. (1981) analyzed the economics of modifying traditional harvesting systems to recover biomass with the use of small chippers or residue balers. Stuart et al. (1981) concluded biomass recovery will most likely utilize chipping and/or baling processes, with balers being economically competitive with chipping systems.

Since harvesting costs are influenced by site specificity, stand characteristics and the physical layout of plantations, the applicability of any given cost analysis to all other situations is often precluded (McKenna 1984). However, a general methodology for defining various financial and energy parameters would be useful in determining approximate costs for certain given situations. Economic analyses may project costs

for productive hours or scheduled hours while others use costs per unit area (McKenna 1984). Miyata and Steinhilb (1981) organized a logging cost analysis system using scheduled and productive hourly costs and costs per mile. This project assigned productive costs per hectare and evaluated these costs as a function of site qualities and stand characteristics under specific management systems.

The harvesting strategies evaluated by this research project included a harvest/chipping and harvest/baling systems. The costs of whole-tree chipping systems have been studied and reported (Massey et al. 1981; Schiess 1984b). The use of a mobile chip harvester was explored by Sirois (1981, 1982). Estimates of the energy characteristics for these systems were available from Bowersox and Blankenhorn (1979), Pimentel (1980), and Pimentel et al. (1981). A harvester/baler system was developed and analyzed by Teel (1983) and Stuart et al. (1983a, b). The costs of the baling scenario were further explored by Schiess (1984a). The technical parameters and energy requirements for the system were provided by Stuart (1984), Blankenhorn et al. (1978) and Pimentel (1980).

Transport Literature Review - The movement of harvested biomass to the point of conversion has been evaluated in a variety of studies (Adler et al. 1978; Mattson 1983; McKenna 1984). Specifically, transport strategies depend on the type of harvester and geometric form of the harvested biomass. In general, transport consists of three phases: (1) movement of harvested biomass to the moment of readiness for long distance transport, (2) long distance haul and (3) movement of biomass from delivery point to conversion process entry point.

Phase one has been further characterized by the eventual form of the harvested biomass. If chipping is employed, some sort of catch basin must be incorporated to retrieve chipped materials and a transfer system devised for movement to the long distance hauler. Sirois (1982) described the technical and financial characteristics of a chip harvester operated in tandem with a forwarder and chip unloader/loader. An alternative to chipping is a whole tree baler. Stuart et al. (1983a, b) envisioned the use of a baler as a necessary complement to specific harvest modes. The harvested trees must be caught, piled, directed to a baler and then to an eventual point of departure. Certain types of trucks have been adapted in forestry operations to load whole trees, thinnings and forest residues (Larsson and Carlsson 1982). This truck equipment is capable of being modified for short-rotation crop use (Marley 1982). Balers might also be outfitted with a knuckleboom loader to aid in material movement to the baler and as a loading device (Schiess 1984a). The costs of the prototype loader can be estimated from well established data on similar equipment (Larsson and Carlsson 1982; Marley 1981; Pimentel et al. 1981). The efficiency of any loader depends upon the size and weight of bales and the loading time. The use of a baler in agriculture is well known and, in forest applications, experimental trials have refined technical requirements and costs for biomass recovery (Stuart et al. 1981; Stuart et al. 1983a; Schiess 1984a).

For purposes of this study, biomass delivery from the plantation site was assumed to involve truck transportation. Since plantations will most likely be established on abandoned farmlands, a network of roads was

assumed to exist. The efficiency of a trucking system depends upon vehicle weights and capacity, plantation production capacity, distance to conversion facility, time required for travel and conversion facility demand (Adler et al. 1978). Cost comparisons among new vehicles, used vehicles and leasing determined the most cost efficient system. Adler et al. (1978) performed such a cost comparison for a 35-truck fleet supplying wood chips to a 50 MW wood-fired power plant in Vermont. The self-ownership and operation of either new or used trucks was the most cost efficient approach in this proposed transportation scenario. This project utilized current costs, capacities and other technical parameters to assess truck transportation and equipment requirements (A.T.A 1982; A.T.A 1984). Energy inputs and consumption for new tractor-trucks and trailer vans were based on well established equipment characteristics (A.T.A 1984) and on energy values summarized in Bowersox and Blankenhorn (1979).

Upon delivery, both chips and bales require unloading and transport to a storage site or conversion point. The former require a system of chip conveyors. The various types of conveyors and their specifications, costs and capacities are readily available from forest equipment manufacturers (Morbark Indus. Inc. 1984). The unloading of bales requires equipment similar to that used in the loading phase. The costs are dependent upon the distance to the storage site, bale size and weight and unloading times.

Harvest and Transport Economic Analyses - Analysis of the harvest and short and long transport of the biomass was approached through a comparison of two distinct strategies: harvest/baling and harvest/chipping. In the harvest/baling strategy, trees were cut, crushed and permitted to dry in the field before being loaded and transported to the storage/conversion site. The second scenario involved simultaneous harvest/chipping operations and the subsequent transport of chips to a storage/conversion site.

The cost comparison between the harvest/baling and harvest/chipping strategies considered the variable effects of machine efficiencies, moisture contents, storage and drying needs and conversion specifications of the respective products. The financial and energy analyses were in keeping with the format used in the prior section of research on plantation production.

Several key operating parameters were established for the economic analysis. All operations were based on a 181 day harvest period extending from the beginning of October to the end of March. The productive time-frame would be 1032 h/yr, based on harvesting 5 days a week, with 2 days set aside for inclement weather, equipment delays and maintenance. Based on this estimate and the wear-out life of equipment, the usage and expected lifetime for harvest and transport equipment for both scenarios were summarized (Appendix C, Table C-4). The number of equipment units was based on the operational capacity of each unit, the annual operating period and the size of the total work assignment. The biomass yields per hectare, before harvest, were taken from the first rotation results from this project's Spruce Creek plantation. Actual processing times and equipment field capacities were established and applied to the biomass output from the project's various strategy/site combinations.

In the harvest/baling strategy (Strategy A) field drying greatly reduced the green field weight of the trees. Stuart et al. (1983a, b) realized moisture contents of less than 20% after crushing and field drying for two days. This analysis used a more conservative 60% reduction of green field weight, providing moisture contents of 20-30%. The weight reduction influenced the processing times of the loader and the baler. A further reduction in net weights was made for losses attributed to the operating efficiency of the baler. Schiess (1984a) found fiber losses approaching 15% when baling a stand of small hardwoods. Fiber recovery was estimated at 90% for this project. In the harvest/chip strategy (Strategy B) the harvester/chipper was also assumed to have a 90% operating efficiency, resulting in a decreased yield of 10%. This harvest efficiency estimate was based on field tests of comparable equipment in high density sites (Sirois 1982).

The cost of the harvest-transport function per oven dry tonne was not significantly different among the individual strategy/site production systems. Although the strategy/site yields varied from 23 to 43 ODt/ha, the standard deviation for the mean cost among these eight options was only 2.3% of the mean. This held for harvest Strategies A and B. Since there was no apparent correlation between the cost per oven dried tonne and the volume per hectare a representative yield of 36 ODt/ha, with a green field weight of 73 t/ha, was used in the cost analyses. The processing times per hectare and the equipment requirements for the two harvesting strategies as applied to the average strategy/site yield of 36 ODt/ha are listed in Appendix C (Tables C-5, 6).

The accounting format was identical to that used in the production phase of this project. Financial and energy costs were first calculated on an hourly basis and then converted to cost per hectare. The key component to this conversion equipment processing times was identified through "field capacity." Thus, processing times multiplied by the hourly costs identified the costs per hectare. The hourly financial and energy costs for equipment in both harvest strategies are reported in Appendix C (Tables C-7, 8) and the financial and energy costs per hectare and per net harvested oven dried tonne for both scenarios are summarized in Appendix C (Tables C-9, 10). The post-harvest yields account for the weight loss from field drying and material loss due to equipment inefficiencies.

In summary, the harvest and transport costs from this project compare favorably to other published findings. The harvest/baling strategy, Strategy A, cost $19.08/ODt and the harvest/chipping strategy, Strategy B, cost $33.30/ODt. These are equivalent to green tonne costs of $9.54 for Strategy A and $16.65 for Strategy B. McKenna (1984) presented a range of costs, in 1983 dollars, for the harvest, processing and transport of wood energy chips of $12 to $25 per green tonne, stump to mill.

Certain costs proved dominant within Strategy A and B. In the harvest/baling strategy, Strategy A, transportation was the largest cost (23.8%) followed by the baling (18.5%), loading/unloading (20.9%) and plant chipping operations (15.9%). In harvest/chipping strategy, Strategy B, the overriding input costs were for the harvester/chipper (42.0%) and its accompaniments (32.5%). These latter costs were also responsible, in large part, for the cost differential between the strategies, $19.08/ODt for

Strategy A versus $33.30/ODt for Strategy B. In conclusion, the smaller scaled harvester/baler system (Strategy A) was the most economical strategy.

Storage Function

Storage Literature Review - The pre-utilization strategy represents the storage and drying requirements of biomass arriving at the conversion site. The specifics of the storage and/or drying alternatives reflect the conversion requirements of the forest biomass.

Biomass plantations will most likely be harvested during fall and winter periods. Since conversion facilities operate year round, the biomass input must be stored. Storage should either incorporate the drying of biomass or at least prevent its extensive rewetting. Five environmental factors that should be addressed in the storage and drying of materials are temperature, humidity, wind, rain or snow, and wind blown dust (Wengert 1977). Losses in available energy due to excessive wetting are known to occur in the outside storage of green hardwood particulate fuels (White et al. 1983b). Saucier and Phillips (1982) also indicate improper storage of wood chips lead to volatile losses, fiber deterioration, and spontaneous combustion. However, woody bales may suffer less degrade in storage than piled green ships (Stuart et al. 1983a).

Several studies reported on the impact of different storage techniques. Chips and wood wastes, in covered versus uncovered storage piles, had significant differences in moisture content (Bulpitt and Walsh 1982). Saucier and Phillips (1982) indicated shed covered fuel chips maximized fuel values and were dryer than uncovered piles. However, the shape of the piles and the length of storage time also influenced moisture levels. White et al. (1983a) found higher wood chip piles had lower average moisture contents. Generally, conical shaped piles were recommended, particularly since flat top piles were known to increase moisture percolation to the internal zones (Bulpitt and Walsh 1982). If a baled form of biomass was stored, certain geometric arrangement of stacks could enhance drying, prevent degrade and control rewetting. Wengert (1977) described yard layout patterns for lumber that may be applicable to bales. Stuart et al. (1983a) noted increased bulk density and stackability of bales increased their yard storage capacity by two-three times over chips.

Storage times are usually dependent on the quantity of incoming material and the subsequent utilization rates. Certain time related parameters have been investigated and can be used as guides for an optimal storage strategy. Storage should not exceed 60 days if the increase in wood fuel moisture content is to be minimized (White et al. 1983a). White et al. (1983b) noted an inverse relation between the average net heating values of green wood chips during the first two to four months of storage and the moisture content of the pile surfaces. Saucier and Phillips (1982) found wood fiber deterioration losses to be significant within the first three months of open storage. Gislerud (1982) showed indoor storage of chips resulted in minimal dry matter losses of 1-1.5% per month after 3-5 months.

The choice of a drying technique for biomass is dependent upon the physical characteristics of the woody material, the intended use for the material

and certain financial considerations. For ethanol production, higher moisture contents are preferred and drying can be preempted. However, it is more efficient to use relatively dry biomass for most end uses (Springer 1979). A multitude of drying procedures has been examined. Air drying lowered or eliminated the risk and occurrence of decay and mold when moisture content was reduced below 22% (Wengert 1977). Frea (1984) compared the cost involved in three methods of drying forest residues to the base value of burning green wood chips and found unheated forced air drying had the most favorable return on its cost investment.

Storage Economic Analysis - The storage of biomass at the conversion site was dependent on the form of the material as it arrived at the site and its subsequent processing specifications. For example, in the production of ethanol, a high moisture content may be desirable. However, with direct incineration, pyrolysis or liquefaction, moisture levels should be below 25% for a higher conversion efficiency. Alternate combinations of storage operations for the pre-utilization of biomass and associated total storage costs are listed in Table 3-4. The materials stored under the "wet" strategies A1, A4, and B1 would be appropriate for ethanol production. A1 and B1 would also be appropriate for pulp production. The remaining strategies incorporate the drying of biomass and thereby fit the needs for direct incineration, pyrolysis, gasification and liquefaction.

Storage costs would depend upon moisture contents which would vary with timing of the harvest and length of time the wood is exposed to the elements after harvest (White and Curtis 1983). Approximately 90% of any decrease in moisture content would occur within the first 6-8 weeks of storage (White and Curtis 1983). Storage technique will affect the drying process.

In most instances storage would take place before direct drying since most harvested materials would not undergo immediate utilization. Types of storage considered were outdoor, both wet and dry, and indoor. The following assumptions were made. First, an average storage timeframe from arrival at the conversion site to the point of utilization was placed at six months. Second, the bale and chip configurations required estimates of their respective storage areas and allied equipment movement areas. Bale size and stack heights were based on recommendations by Schiess (1984b). Chips were based on the conical dimensions presented in Saucier and Phillips (1982).

The financial and energy costs/ODt for storage of woody biomass are reported in Appendix C (Table C-11). Common costs included land rent, property tax and insurance. Other costs were characteristic of the particular storage technique. For example, in the wet storage strategies (A1, A3, A4, B1 and B3) the materials were piled without shelter or coverings. However, Springer (1979) pointed to the need of rotating green chips on a regular basis to prevent spontaneous combustion. Thus the green chip strategies A1, B1 and B3 included a rotation cost. The final movement of bale and chip materials to the conversion plant was included in the storage cost.

Financial and energy costs/ODt for drying of wood biomass are listed in Appendix C (Table C-12). In Strategies A2 and B2 the dry storage of green wood chips required use of a heavy polyethelene film. This

Table 3-4. Total storage costs for woody biomass.

Strategy	$/ODt	10^6 kcal/ODt
Bales		
A1[1/ 3/] chip, wet storage	8.61	0.056
A2[2/] chip, dry storage, dry	14.73	0.023
A3[2/] wet storage, dry	29.31	0.101
A4[1/] wet storage	4.29	0.075
Chips		
B1[1/ 3/] wet storage	8.90	0.058
B2[2/] dry storage, dry	15.02	0.025
B3[2/] wet storage, dry	24.35	0.074
B4[2/] dry, dry storage	15.93	0.051

[1/] Appropriate for fermentation processing.

[2/] Appropriate for direct incineration, pyrolysis, gasification and liquefaction processing.

[3/] Appropriate for pulp processing.

technique has proven less costly than using silos or other shelters (Springer 1979). Strategy cost included film, its application and removal, and chip movement to the conversion plant.

The stored biomass in the "wet" strategies A1, A4, and B1 was subsequently moved direct to the conversion site. However, in the other strategies, a drying process followed storage. The technical parameters and cost estimates for the unheated forced air system were based on the study conducted by Free (1984). Drying costs were a function of the moisture content reduction in the woody biomass.

In certain strategies drying was accomplished prior to storage. Springer (1979) noted wood dried below its fiber saturation point (20-24% moisture content) was not subject to bacterial or fungal attack. Strategy B4 dried the biomass prior to covered storage.

Overall, storage costs ranged from $3.97 to $8.90/ODt (Appendix C, Table C-11). With uncovered chip piles (A1, B1 and B3) costs approached $9.00/ODt due to the rotation of materials over a prolonged storage period. Covered chipped materials (B2) eliminated the expense of rotation and ranged from $4 to $6/ODt. Uncovered storage of bales (A3, A4) held at $4.29/ODt largely on the basis of limited maintenance operations. Indoor storage of chips (B4) was the lowest cost system ($3.97/ODt) due to reduced handling costs.

Drying was more expensive than storage. The lowest cost alternatives (A2, B2) at $9.14/ODT were associated with dry storage and the minimization of moisture pick-up prior to the final drying step. Uncovered biomass (A3, B3), due to its maximum moisture gain, was the most expensive to dry ($15.45/ODt). Bales proved more costly to dry than chips due to higher moisture sorption during storage ($25.02/ODt).

Total storage costs ranged from $4.29/ODt to $29.31/ODt (Table 3-4). For fermentation (i.e., ethanol production) strategy A4 ($4.29/ODt) was recommended over the more expensive alternatives A1 and B1. While baled material cost less to store than chipped material, it may also be more difficult to process. For direct incineration and other conversion strategies dependent on the moisture content of its feedstock the dry storage and drying strategies of A2 and B2 and B4 were the most economical at an approximate cost of $15/ODt. The highest cost strategies were A3 and B3 at $25 and $30/ODt, respectively.

Cost Summaries for Supplying Biomass to Conversion Center

The economic rationale for using a particular type of biomass within a conversion process is dependent on the technical properties of the input, the ability to supply a given rate and volume of input and the total supply cost of the material at the conversion site. Various aspects of this project have identified the physical and chemical properties of the hybrid poplar product. Furthermore, the commercial design for a plantation system has been proposed as 4 units (924 ha/unit) to insure efficient use of various equipment items and to also maintain a constant annual supply of output from the plantation. As a final component to this economic analysis, the cost of supplying biomass will be presented as a summation of

all expenses incurred within plantation production, harvesting and transport and the materials storage at the conversion site.

The following cost summary includes selected strategies from each of the three central stages of the supply process: production, harvest/transit and storage. Production costs are based on two least cost strategy/site combinations: Basher control and Basher fertilization. These combinations had production costs of $29/ODt (control) and $36/ODt (fertilization) on a before harvest basis. It should be noted that the control strategy on the Morrison site also fell within this range ($32/ODt), with the Morrison fertilization strategy outside this range ($44/ODt). The irrigation and fertilization/irrigation strategies are not included within this total supply analysis due to their extreme production costs. These strategies ranged from $85/ODt (Basher, fertilization/irrigation) to $104/ODt (Morrison, irrigation), on a before harvest basis. As such, their production costs were double to triple those from the control or fertilization strategies.

Although the control strategy on the Basher site was nearly $7/ODt cheaper than the Basher fertilization strategy on the same site, there remains some question as to whether the control strategy's nutrient drain would permit the same output over continued rotations. Potentially, fertilization may be required to sustain the volume from a plantation system.

Both harvesting strategies were included within the supply cost summaries as examples of a least cost, but largely developmental, system proposed by Stuart et al. (1983a, b) and of a more expensive but commercially available harvest system. Finally, two opposing storage strategies were incorporated within the cost summaries to meet alternate material specifications. The conversion of biomass to ethanol via hydrolysis/fermentation would show preference to "green" storage, thus assuring biomass with high moisture content. In contrast, conversion of biomass to energy via direct incineration, pyrolysis, gasification and liquefaction would place a priority on biomass with a moisture content ≤ 20% through dry storage.

The assembly of the various alternate strategies within each of the 3 stages provides 8 supply systems:

#1	Basher-control	Harvest/baler	Wet storage
#2	Basher-control	Harvest/baler	Dry storage
#3	Basher-control	Harvest/chipper	Wet storage
#4	Basher-control	Harvest/chipper	Dry storage
#5	Basher-fertilization	Harvester/baler	Wet storage
#6	Basher-fertilization	Harvester/baler	Dry storage
#7	Basher-fertilization	Harvester/chipper	Wet storage
#8	Basher-fertilization	Harvester/chipper	Dry storage

In addition to this cumulative analysis of supply costs, a further study was made on the origin of cost within the various strategies. Origin, in this instance, refers to the proportions of total input cost from capital, fuel and materials, labor and land. These basic expenses were identified within each stage of the supply system and over the cumulative system. This provides a measure of the relative dependence on particular inputs within each stage and over an entire supply system.

Financial Costs for Total Supply Systems

The range in the total financial cost for hybrid poplar chips was $59.57 to $87.86/ODt (Appendix C, Table C-13). The minimal cost system was composed of the least cost strategies of control production, the harvest/baler system and wet storage of "green" chips. The maximum cost system utilized fertilization production, harvest/chipper equipment and the storage of chips dried to a 20% moisture content.

In the least cost scenario (System #1), 54% of the total supply cost originated from biomass production, 32% from harvesting and the remaining 14% from storage. The biomass production cost of $31.89/ODt was distributed as 27% in capital/fuel/materials, 37% in labor and 36% in land.

The harvest and storage stages within System #1 were dominated by capital, fuel and material costs. In the harvest/baler system, 76% of the $19.08/ODt harvest cost originated from capital, fuel and materials and 24% from labor. Green storage added a final charge of $8.60/ODt, with 76% capital-related and 24% tied to labor. From a composite view, nearly 50% of the total supply cost of $59.57/ODt in System #1 was developed from capital and material inputs, 31% from labor and 19% from land.

As the least cost supply system was upgraded toward technically more sophisticated alternates using fertilization, harvest/chipper and dry storage, the system became more expensive and more dependent on capital. The fertilization strategy increased production costs by $7.65/ODt. Since 98% of this additive practice was tied to materials and capital, the total strategy (establishment, maintenance and fertilization) had 50% of its total cost in capital and materials, 26% in labor and 24% in land (Appendix C, Table C-13, System #5).

In like manner, the shift from the smaller scale and less capital-intensive harvest/baler system to the larger scaled harvest/chipper system increased harvest costs by $14.22/ODt, with 96% of the increase tied to capital. The conversion from wet storage to dry storage increased costs by $6.42/ODt, with 77% derived from capital and material inputs.

In the most expensive supply system, involving all changes within each of the three phases, biomass would cost $87.86/ODt (Appendix C, Table C-13, System #8). This increase of $28.29/ODt over the least cost system largely stemmed from the addition of new capital and materials. This system was financially composed of 67% from capital and material inputs, 21% from labor and 11% from land. In addition to being the most expensive supply system it was dominated by the capital and material cost sector.

An overview of the various supply systems is provided in the financial summaries of the least cost and maximum cost options (Table 3-5). For both systems, the requirements of harvest and storage proved to be the dominant expenses. Within the least cost approach (System #1), harvest was 32% of the total supply cost and storage was 14% of the total. For the maximum cost approach (System #8), harvest and storge were 38% and 17%, respectively, of total cost.

Table 3-5. Financial cost comparisons of stages within the least cost and maximum cost biomass supply systems.

Stage	Least Cost (System #1) cost/ODt	% of total	Maximum Cost (System #8) cost/ODT	% of total	Cost Increase cost/ODt	% of total
Plantation Production	31.89	53.5	39.54	45.0	7.65	27.0
Harvest	19.08	32.0	33.30	37.9	14.22	50.3
Storage	8.60	14.4	15.02	17.1	6.42	22.7
Total	59.57	100.0	87.86	100.0	28.29	100.0

This dominance of harvest and storage was further identified by their relative cost increases between the two systems. The total cost differential between system #1 and #8 of $28.29/ODt was created from the increases of $7.65/ODt in production, $23.58/ODt in harvest and $6.42/ODt in storage. As such, over 70% of the total increase originated from the harvest and storage stages of the supply system. This impact was also shown by the relative cost increase of 24% between the two production strategies versus the 75% increase evident between the harvest strategies and the 75% increase in the storage strategies.

The cost of supplying biomass, in the context of a total system and for these specific alternates, was largely dominated by the harvest and storage components of the systems. Although these components were outside the main focus of this research project, their relative cost impacts emphasize the need for research and development in these aspects of biomass production.

Energy Costs for Total Supply Systems

The range in total energy costs for the eight supply systems was from 1.692 to 1.817 x 10^6 kcal/ODt. The least cost energy alternative involved control production, the harvest/baler system and dry storage. Of interest, the least cost storage strategy involved dry material. Although additional energy was required in the drying of green chips, green chip storage used even more energy for the mechanical rotation of chip storage piles to prevent internal combustion and decay losses.

The least cost supply system (Appendix C, Table C-13, System #2) was dominated by land's energy cost, representing 83% of the total cost per oven dry tonne. As previously referenced, this particular input cost represents land's net energy potential in its alternative employ of corn production. It is an opportunity cost rather than an actual expenditure of energy within the system. Furthermore, since the magnitude of land's energy cost tends to mask both the size of the other energy inputs and the relative importance of shifts in these inputs, land's energy cost was excluded from the following analyses.

Accordingly, the actual energy expenditures within the least cost supply system, less land's energy cost, amounted to 290 x 10^3 kcal/ODt. For this net amount, 16% originated from production, 77% from harvest and 7% from storage. The primary source of these energy inputs was fuel cost, representing 87% of the actual energy input.

Additional energy was used by the strategy shifts to fertilization, the harvest/chipper equipment and green storage. Fertilization caused the greatest increase of energy, using an additional 319 x 10^3 kcal/ODt. Nearly 100% of this increase was for fertilizer itself. The larger scaled harvester/chipper equipment required an addition of 15 x 10^3 kcal/ODt, with most of this involved in the added energy cost for capital. Finally, the shift from dry storage to wet storage used additional energy amounting to 33 x 10^3 kcal/ODt. This energy increase was primarily for capital.

In comparing the most expensive energy supply system (fertilization, harvester/chipper, wet storage) to the least expensive (control, harvest/baler, dry storage), net of land's energy cost, the former required 649 x 10^3 kcal/ODt and the latter 290 x 10^3 kcal/ODt. Ninety percent of the added energy used by the more expensive system was from materials and fuel, with fertilizer being the key ingredient.

The relationship of energy to financial costs throughout the various stages of the two opposing supply systems is presented in Table 3-6. Both cost systems exclude land in order to better define the cost characteristics of all other inputs. It should be noted, however, that the ratio of land's energy cost to its financial cost was the highest for any of the inputs - 122.5 x 10^3 kcal/$1. This ratio indicates that corn production is a relatively inexpensive source of net energy gain per dollar of marketable output. This high energy gain is due to the structure of the energy accounting system. Basically, the total net energy gain from corn production is allocated to land as an energy rent. As such, the large net cumulation of solar energy from the photosynthetic process is attributed solely to the land resource.

The composite energy ratios in Table 3-6, net of land, within the various stages of System #1 ranged from 1.7 to 11.7 (10^3 kcal/$1). Plantation establishment and maintenance ratios were low (1.7 and 2.8, respectively) and referred to the use of relatively high cost energy forms. The key "high cost" input was labor, which had a near non-measureable energy input and yet represented nearly 40% of the financial cost input.

In contrast, the harvest and storage stages had ratios of 11.7 and 6.2, respectively. To a large degree, these higher ratios identified the substantial increase of fuel inputs to harvest and storage and a lesser dependence on labor. Fuel was a less expensive source of energy input and carried a ratio value of 32.

The maximum financial cost system (System #8) provided a further view of the energy ratio effects from the three system changes (fertilization, harvest/chipper and dry storage). These ratios were dominated by fertilization - 24.5 and harvest - 7.1. Fertilizer was a relatively inexpensive form of energy and, as a material input alone, had a ratio of 32.1 The lower ratio for the more complex harvest/chipper strategy

Table 3-6. Energy to financial comparisons of stages within the least cost and maximum cost biomass supply systems (excluding land costs).

Stage		Least Cost (System #1)			Maximum Cost (System #8)		
		10^3 kcal/ODt	$/ODt	10^3 kcal/$	10^3 kcal/ODt	$/ODt	10^3 kcal/$
Plantation	Establishment	17	9.89	1.7	14.	8.22	1.7
	Maintenance	30	10.54	2.8	25.	8.76	2.8
	Fertilization				319.	13.02	24.5
Harvest		223	19.08	11.7	238.	33.30	7.1
Storage		53	8.58	6.2	20.	14.97	1.3
Total		323	48.09	6.7	616.	78.27	7.9

identified a relative increase in capital equipment that, in turn, carried a lower ratio. The marked reduction in the energy ratio for dry storage, versus wet storage, was caused by an absolute decrease in energy inputs and an opposing increase in financial costs. In short, although less energy was used in dry storage it was a relatively more expensive form of energy.

For all of System #8, the ratio 7.9 (versus 6.7 in the alternate system) resulted from a greater increase in energy input than in financial costs. Basically, this final system was a more expensive proposition from both an energy and financial viewpoint. Energy input increased by 91% and financial costs by 63%. However, the additional input of 293 x 10^3 kcal/ODt was a relatively less expensive form of energy than used in the base supply system. This was largely caused by the addition of fertilization to the supply system.

Conversion Function

Conversion of forest biomass into useful energy may take a variety of pathways from direct incineration (direct fire) to gasification, liquefaction or conversion to chemicals including ethanol. Many of these methods have not been used in large-scale operations; and, as a result, engineering operating parameters are not available for comparisons.

There are many methods to produce chemicals from lignocellulosic material. Many of these methods at present do not compare economically to production of chemicals by the petrochemical industry (USDA 1975). An integrated plant for producing heat, electricity and chemicals from wood is technically feasible and may be economically feasible in the future.

One technique of converting biomass to chemicals is to hydrolyze cellulose to produce glucose which can be fermented into ethanol (USDA 1975; National Academy of Sciences 1976; USDA 1975; Oshima 1965; Dreger 1976; Zinkel 1975; Goldstein 1975). Hemicelluloses found in wood are not crystalline and hydrolyze readily into sugars Upon hydrolysis, the predominant hemicellulose in softwoods yields hexose sugars which can also be fermented into ethanol. On the other hand, hydrolysis of the hemicelluloses in hardwoods yields large quantities of pentose sugars which can be converted into furfural by acid treatment (National Academy of Sciences 1976). Lignin in wood consists of aromatic components and can be used to produce benzene and phenol (National Academy of Sciences 1976). Other conversion processes for biomass may be used to produce methanol (Wan 1984). All of these chemicals, particularly ethanol, can be used to produce energy or as a feedstock for the chemical industry.

Forest biomass can be converted into a burnable gas by pyrolysis (Hammond et al. 1974; Knight et al. 1976; Tatom et al. 1975; SERI 1979; SERI 1980a; SERI 1980b; SERI 1980c; SERI 1984). The type and quantity of gases evolved during pyrolysis depend not only on the type and condition of the wood substance, but also on the method of pyrolysis. In an inert atmosphere the solid pyrolytic residue is carbon. This can be used to produce carbon monoxide which can be combined with hydrogen in the presence of a catalyst at high temperatures and pressures to obtain synthetic gas, methanol or both (National Academy of Sciences 1976; Reed and Lerver 1973; Hammond et all 1974).

Liquefaction can be used to convert wood to oil and hydrocarbon fuels (National Academy of Sciences 1976; Appell et al. 1971; Anderson 1972; Heineman 1954). These processes usually require a catalyst, temperatures of about 500 C and pressures up to about 34 x 10^3 kPa. About 90% conversion of cellulosics to oil has been reported using various temperatures, pressures, and catalysts (Appell et al. 1971; Anderson 1972; Heineman 1954). This synthetic oil has a fairly high heat content and can possibly be further refined using present technology (Appell et al. 1971; Anderson 1972; Heineman 1954).

Direct incineration is currently the most widely used method of wood energy conversion. Fluidized bed burners, suspension burners, spreader-type stokers, chain grate stokers, Dutch ovens, cyclone burners and combined systems are all presently being used to incinerate wood (Bogot 1976).

Pyrolysis, gasification, liquefaction, or direct incineration conversion systems coupled with a high pressure boiler or high pressure boiler with a superheater connected to a steam turbine and generator could be used to generate electricity from forest biomass (Babcock and Wilcox Co. 1975; Bogot 1976). Direct incineration was chosen for this evaluation because it is presently the most commonly used technique. If another primary conversion process such as pyrolysis is used, the evaluation would have to be adjusted to take into account changes in efficiencies and other conversion considerations.

Wood has certain inherent advantages as a fuel: low ash content, ignitability, almost no sulfur content and renewability. Disadvantages of using wood as fuel include moisture content, particulate discharge, gross heat value per unit volume, availability in certain locations, material handling and storage.

Important forest biomass combustion parameters include particle size, moisture content, gross heat of combustion, usable heat, proximate analysis and ultimate analysis. Particle size will influence combustion rate, steam production, particulate emission, fuel feed rates, rate of excess air application and combustion efficiency (Babcock and Wilcox Co. 1975; Bogot 1976; Johnson 1975; Koch 1972). Variation in particle size would require a very versatile combustion system. It is much more efficient to use particles of a specific size for maximum utilization of the wood as a fuel.

Another consideration in combustion is usable heat from the burning of wood. In general, the moisture-free ultimate analysis (elemental composition) of various wood species indicates a fairly uniform carbon content of approximately 50%, hydrogen content of approximately 7%, oxygen content of approximately 43% and ash content of approximately 1% (Babcock and Wilcox Co. 1975; Corder 1973: Bogot 1976; Koch 1972; Mingle and Bouble 1968; Lenk 1970). Wood oven dry gross heat of combustion values range from 18 to 22 MJ/kg, depending on species (Babcock and Wilcox Co. 1975; Blankenhorn et al. 1985; Bowersox et al. 1979; Virtanen 1963; Bogot 1976; Lenk 1970; Murphey and Cutter 1974; Howard 1973; Karchesy and Koch 1979).

Proximate analysis of a fuel indicates the amount of volatile material and fixed carbon in the fuel. Wood and bark possess about 80% volatile

material and 20% fixed carbon on a dry weight basis (Babcock and Wilcox Co. 1975; Corder 1973; Virtanen 1963).

The usable heat or recoverable heat from the burning of wood indicates how much wood needs to be burned to produce a certain amount of energy input to a boiler. When the hydrogen in wood is burned, it combines with oxygen to form water and carries heat up the stack (Koch 1972). In the burning of 1 kg of dry wood about 0.6 kg of water is formed, requiring an energy input (Koch 1972). Other stack gases (carbon dioxide, nitrogen and excess air) may carry energy up the stack (Koch 1972). Hence, the usable heat of oven dry wood is the gross heat of combustion of wood minus heat losses associated with hydrogen combustion and other stack gases.

In addition, sorbed water in wood represents an energy loss (Koch 1972) because it takes energy to remove moisture before or after the wood enters the combustion chamber. For efficient control of combustion, it is important that the wood be as dry as possible before entering the combustion chamber because the energy required to remove the moisture in the combustion chamber would then be supplied by the burning of biomass. This will increase the amount of wood necessary to satisfy a given energy input to the boiler.

General considerations for electrical power generation, from the standpoint of design, include: steam pressure and temperature, degree of superheat, turbine efficiency, fuel source availability, cost and trends, steam requirements, heat transfer apparatus, fuel feed rate (MJ/hr), boiler feed-water, building space, geographical considerations, environmental restrictions, energy required for auxiliary equipment, operating personnel, efficiency and others (Babcock and Wilcox Co. 1975; Bogot 1976). These considerations must be analyzed for every power plant for any fuel source.

After the energy is converted to steam at the boiler, the transformation of the steam into electricity will probably require similar equipment regardless of the fuel. This implies that one of the major cost differences between a wood-fired electrical plant and a fossil-fuel power plant will be in the combustion system and boiler. The installation costs of a coal and wood fuel boiler system are about three and four times, respectively, the cost of a fuel oil or natural gas system. Thus, the initial cost of a wood-fired plant will be more than an oil or gas-fired plant and somewhat similar to a coal-fired plant.

The operational parameters and financial costs for all of the potential conversion strategies are presented in Appendix C (Table C-14). Electricity generation via direct incineration in a power plant and ethanol production are the two conversion alternatives used in the net financial and energy analyses. These conversion processes are used because of the relatively low energy yields and higher financial costs associated with the other conversion strategies. Direct incineration is currently the most widely used method of wood energy conversion and ethanol is an extremely versatile fuel (Appendix C, Table C-15).

Ranges in the estimated energy content and yield of products are summarized in Appendix C (Table C-15). The values presented represent differences in the conversion processes. For example, pyrolysis, gasification and

liquefaction have lower available energy after conversion to an intermediate energy product than direct incineration. However, the advantages of eliminating fungal degradation concerns, use of existing combustion systems (coal-fired furnaces), transportation systems (pipelines, etc.) and utilization of secondary fuels/chemical feedstocks may offset, in certain future situations, their reduced energy yield as compared to direct incineration.

SRIC biomass offers the advantage of supplying similar genetic material with a lower variability in the properties among trees. Ethanol represents one of the more versatile intermediate woody biomass conversion products because it can be easily stored, transported and used as a fuel or as a chemical feedstock. Estimates of ethanol recovery based on biomass yields in Task 2 are presented in Appendix C (Table C-16).

Estimates of the fuel and energy potential from the biomass by management strategy were obtained by combining the biomass yield, fuel and chemical values from Task 2. The goal of these calculations was to estimate the amount of electricity (kwh) and secondary fuels (e.g., ethanol) available from the four year old biomass.

Since the wood and bark have different gross heat of combustion and chemical content values for each management strategy, the four year old biomass yields were divided into percentages of wood, bark and branchwood. Total tree biomass was determined to be about 70% wood, 15% bark and 15% branchwood for all management strategies based on the four year old data in Table 2-15.

The four year old gross heat of combustion values for wood, bark and branchwood (wood/bark) for each management strategy were combined with the percentages of wood, bark and branchwood in the total tree to obtain a weighted gross heat of combustion value for the total tree. The following gross heat of combustion values were used for calculating the energy potential in the biomass: 1) Basher; control - 4620 cal/g, irrigation - 4649 cal/g, fertilization - 4607 cal/g and fertilization/irrigation - 4608 cal/g and 2) Morrison; control - 4680 cal/g, irrigation - 4657 cal/g, fertilization - 4635 cal/g and fertilization/irrigation - 4603 cal/g. The biomass yields (ODt/ha), reduced by 10% because of losses during harvesting, transport and storage, were combined with the gross heat of combustion values to estimate the maximum energy content per hectare. This value was reduced to usable heat content to account for hydrogen combustion, stack gas losses and 20% moisture content (Koch, 1972) and converted to kwh/ha for each management strategy (Appendix C, Table C-16).

Neenan (1984) reported that present conversion of woody biomass to C_5 and C_6 sugars is about 30% efficient, and about 50% of C_5 and C_6 sugars can be converted to ethanol. Number of liters of ethanol per hectare by management strategy was estimated (Appendix C, Table C-16) by applying the conversion efficiencies listed above to total tree biomass yields and using a specific gravity of ethanol of 0.79 g/cc. A number of processes can be used to produce ethanol (Neenan, 1984; Wright and d'Agencourt 1984). Each process will require a different biomass moisture content and each process assumes the biomass will be delivered wet (Neenan, 1984; Wright and d'Agencourt 1984).

Net Financial and Energy Analysis

The net financial and energy analyses were conducted for two alternative energy products - electricity or ethanol (Appendix C, Tables C-16 to 20). These analyses were based on financial costs per kwh and per liter of ethanol and the energy costs were based on kcal/ha.

The conversion to electricity was calculated on the basis of burning the fuel at 20% moisture content and using a 90% net biomass yield after harvest, transit and storage. The financial and energy input costs required to produce electricity from biomass were compared with electricity outputs (valued at $0.046/kwh and in kcal/ha). A similar comparison was made for ethanol production. All of the net values for producing electricity and ethanol were negative.

The net delivered biomass financial and energy costs to the electric generating facility per kwh and kcal/ha were higher for all management strategies than the selling price of $0.046/kwh and the net kcal/ha output of electricity. Greater than 50% of the costs for the electricity were associated with net biomass fuel input costs at the electrical plant. The biomass production costs associated with each management strategy were 40 to 70% for the financial costs and greater than 80% for the energy costs of the delivered net biomass. Reduction in the first rotation production costs or increasing the first rotation yield may help reduce the overall costs.

Including the electric generating plant costs increased the net loss. This is associated with the conversion efficiency of biomass to electricity. Pyrolysis, gasification and liquefaction will provide increased input costs, compared to direct incineration of biomass for electricity generation, thus producing a larger net loss.

Converting wood to ethanol for use as a secondary fuel or chemical feedstock provided an interesting alternative to electricity. While the net financial and energy costs were negative for all management strategies (Appendix C, Tables C-16 to 20), the net values for control and fertilization strategies (both sites) were close to breaking even for the financial analysis. These net values were based on: 1) the current list price for fermented ethanol (Chemical Marketing Reporter, May 13, 1985); 2) the estimated plant costs (excluding feedstock costs) of $.196/ℓ of ethanol for a plug-flow, dilute-acid, high-temperature hydrolysis plant including a by-product credit of $.109/ℓ (Wright and d'Agincourt 1984) and 3) the present yield of ethanol from woody biomass (Neenan, 1984).

Additional research may improve the outlook for producing ethanol from woody biomass. Two alternative research approaches appear to be feasible. The first approach would include reducing the $/ODt and kcal/ODt by reducing the costs, increasing the biomass yield per unit cost or both. Another approach would be to increase the yield of ethanol per unit weight of woody biomass. The goal of current research and development efforts is to convert 65-70% of the wood to fermentable sugars by improving process yields through: 1) fermentation of five carbon sugars to ethanol, 2) improved fermentation and distillation efficiencies, 3) pretreatments to fractionate the feedstock, 4) optimization of acid hydrolysis concepts and

5) exploratory research and development projects in enzymatic schemes (Neenan, 1984). These projects are designed to improve processing so that up to 70%, most of the cellulose and hemicelluloses, of the wood can be converted to fermentable sugars. A 70% conversion efficiency, coupled with an increase in the production of biomass and a decrease in the costs of biomass production, may promote the use of wood as a feedstock to ethanol.

A summary of the total financial and energy costs for conversion to electricity and ethanol using biomass from the Basher control and fertilization management strategies is given in Tables 3-7 and 3-8, respectively. The financial costs for both management strategies are similar in that of the total costs for electrical production; about 19% is for biomass production, 27% for harvest/transport and storage and 54% is for plant costs. For ethanol conversion, biomass production accounts for about 38%, harvest/transport for about 22% and plant costs for about 40% of the total product costs. It appears that for these two conversion strategies biomass production financial costs are about one third of the total product costs. It is difficult to conduct a similar analysis on the energy data (Table 3-8) because plant energy costs are unavailable and land energy costs are high.

The influence of land costs in these analyses, particularly in the energy analysis, is evident. Removal of the land costs (44.316×10^6 kcal/ha) and excluding the plant energy costs from the analyses produces positive net energy for electricity and ethanol production. However, removing the land costs ($361.66/ha) still produces a negative financial balance which is higher for electricity than ethanol production.

Examination of the financial and energy balances for the management strategies indicates all the strategies produce negative results for the production of electricity. The control and fertilization strategies produce the most promising results for the conversion of SRIC forest biomass to ethanol. Additional improvements in SRIC biomass yields, reduction in costs per unit weight of biomass and increases in the ethanol yield from forest biomass may promote the conversion of SRIC forest biomass to ethanol.

Sensitivity of Biomass Production and Conversion Strategies to Alternate Costing Assumptions

Biomass Production Financial Sensitivity Analysis - The relative impact on total biomass production costs from changes of ±10% to selected input costs and biomass yields was analyzed for each site/management strategy combination. Each factor listed below was altered with the remaining input costs and yields, in terms of operation, rates and timing, held constant.

1. Capital - changes to current cost may reflect either lower or higher costs in terms of equipment use, initial prices and/or carrying charges.

2. Fertilization - changes may reflect a decrease in the volume of fertilizer (assuming that such reductions would not affect biomass output) or, alternatively, a pending increase in price for such materials.

Table 3-7. Summary of financial electricity and ethanol production[1/] costs for Basher control and fertilization management strategies.

Operation	Basher Control Costs Biomass Yield at Conversion Site[2/] 31.81 ODt/ha			Basher Fertilization Costs Biomass Yield at Conversion Site[2/] 38.26 ODt/ha		
	Electricity Generation					
	$/ODt	$/kwh[3/]	% of Total	$/ODt	$/kwh[3/]	% of Total
Establishment[4/]	10.04	0.007	6	8.35	0.005	4
Maintenance[4/]						
Property Rental and Tax	11.37	0.007	6	9.45	0.006	5
Other	10.49	0.007	6	8.72	0.006	5
Cultural Amendment[4/]	--	--	0	13.03	0.009	7
Harvest and Transport[5/]	32.39	0.021	18	38.96	0.026	20
Storage[5/]	14.61	0.010	8	17.57	0.012	8
Plant Costs[6/]	101.84	0.067	56	101.84	0.067	51
Total	180.74	0.119	100	197.92	0.131	100
	Ethanol Production					
	$/ODt	$/ℓ[7/]	% of Total	$/ODt	$/ℓ[7/]	% of Total
Establishment[4/]	10.04	0.053	12	8.35	0.044	8
Maintenance[4/]						
Property Rental and Tax	11.37	0.060	13	9.45	0.050	10
Other	10.49	0.055	12	8.72	0.046	9
Cultural Amendment[4/]	--	--	0	13.03	0.069	13
Harvest and Transport[5/]	18.56	0.098	21	22.32	0.118	23
Storage[8/]	--	--	0	--	--	0
Plant Costs[9/]	37.17	0.196	42	37.17	0.196	37
Total	87.63	0.462	100	99.04	0.523	100

Table 3-7. (continued)

1/ Averaging over all sites and management strategies, one ODt of woody biomass yields 1.52×10^3 kwh (divide electrical energy output (kwh/ha) by biomass yield at conversion site (ODt/ha) from Appendix C, Table C-16) and 189.65 ℓ of ethanol (Appendix C, Table C-16).

2/ Yield after fiber loss from harvesting operations.

3/ Divide cost/ODt by 1.52×10^3 kwh/ODt (from Footnote 1).

4/ From Tables 3-1 and 3-2. Financial values ($/ha) were capitalized to the end of the first 4 year rotation and divided by the corresponding site-management strategy yield (ODt/ha). Energy values (kcal/ha) were also divided by the appropriate yield value (ODt/ha).

5/ Strategy B2, from Tables 3-4 and Appendix C (Tables C-9, 10).

6/ Plant costs for a wood-fired power plant, including fixed and variable costs, are $0.067/kwh (Skelton *et al.* 1982). Multiply plant costs (cost/kwh) by electricity yield (kwh/ODt) listed in footnote 1 to get cost/ODt.

7/ Divide cost/ODt by 189.65 ℓ of ethanol (from Footnote 1).

8/ Storage costs are included in plant costs.

9/ Wright and d'Agincourt (1984) recommend for aspen a plug-flow, dilute-acid, high-temperature hydrolysis plant with plant costs of $0.196/ℓ of ethanol. These plant costs include fixed, variable, operations and maintenance costs and a by-product credit of $0.109/ℓ of ethanol. Multiply plant costs (cost/ℓ) by ethanol yield (ℓ/ODt) listed in Footnote 1 to get cost/ODt.

Table 3-8. Summary of energy electricity and ethanol production[1/] costs for Basher control and fertilization management strategies.

Operation	Basher Control Costs Biomass Yield at Conversion Site[2/] 31.81 ODt/ha		Basher Fertilization Costs Biomass Yield at Conversion Site[2/] 38.26 ODt/ha	
	Electricity Generation			
	10^6 kcal/ODt	10^3 kcal/kwh	10^6 kcal/ODt	10^3 kcal/kwh[3/]
Establishment[4/]	0.023	0.151	0.019	0.013
Maintenance[4/]				
Property Rental and Tax	1.393	0.916	1.158	0.762
Other	0.030	0.197	0.025	0.016
Cultural Amendment[4/]	--	--	0.322	0.212
Harvest and Transport[5/]	0.232	0.153	0.278	0.183
Storage[5/]	0.024	0.016	0.029	0.019
Plant Costs	NA	NA	NA	NA
	Ethanol Production			
	10^6 kcal/ODt	10^3 kcal/ℓ[6/]	10^6 kcal/ODt	10^3 kcal/ℓ[6/]
Establishment[4/]	0.023	0.121	0.019	0.100
Maintenance[4/]				
Property Rental and Tax	1.393	7.345	1.158	6.106
Other	0.030	0.158	0.025	0.132
Cultural Amendment[4/]	--	--	0.322	1.698
Harvest and Transport[5/]	0.218	1.149	0.264	1.392
Storage[7/]	--	--	--	--
Plant Costs	NA	NA	NA	NA

Table 3-8. (continued)

1/ Averaging over all sites and management strategies, one ODt of woody biomass yields 1.52×10^3 kwh (divide electrical energy output (kwh/ha) by biomass yield at conversion site (ODt/ha) from Appendix C, Table C-16) and 189.65 ℓ of ethanol (Appendix C, Table C-16).

2/ Yield after fiber loss from harvesting operations.

3/ Divide cost/ODt by 1.52×10^3 kwh/ODt (from Footnote 1).

4/ From Tables 3-1 and 3-2. Financial values ($/ha) were capitalized to the end of the first 4 year rotation and divided by the corresponding site-management strategy yield (ODt/ha). Energy values (kcal/ha) were also divided by the appropriate yield value (ODt/ha).

5/ Strategy B2, from Tables 3-4 and Appendix C (Tables C-9, 10).

6/ Divide cost/ODt by 189.65 ℓ of ethanol (from Footnote 1).

7/ Storage costs are included in plant costs.

3. Fuel - changes may reflect potential decreases in volume through more fuel-efficient equipment or, alternatively, increased fuel prices.

4. Labor - changes to current labor costs may reflect possible decreased labor needs or, alternatively, increased wages and/or hours of labor employed.

5. Land - changes to current land rent and taxes may reflect decreased or increased prices and competition for land.

6. Biomass Yield - the predicted levels of output from the original research findings may be altered to reflect poorer growing conditions or, alternatively, improved growing conditions, improved matching of species with site and/or the use of improved clonal varieties of Populus spp.

The impact of cost changes in basic inputs on the total production cost on an oven dry tonne basis were linear and generally consistent between the two sites (Basher and Morrison), but did vary among the various strategies (Table 3-9). Changes to input costs had the same relative impact on total biomass production costs for the control strategy on both sites due to the identical character of their total cost functions. For the control strategy, labor and land were the more critical inputs. Cost changes of 10% to labor would cause a 3.7% change in the production cost of biomass. A 10% change in land costs would induce a 3.6% change in the total production cost. Capital and fuel inputs had a lesser influence on production cost, with 10% changes to either input causing an 0.7% change to product cost for capital and an 0.3% change for fuel. Since fertilizer was only involved in the control strategy by way of the nursery cuttings and not within the strategy itself, a 10% change in fertilizer cost resulted in an 0.03% change to product cost.

For the fertilization strategy, a cost change to fertilizer had the greatest effect on production costs among all input cost changes. On the Basher site, a 10% cost change to fertilizer caused a 3.0% change in product cost and, on Morrison, a 4.9% change in product cost. The larger impact on the Morrison site reflects the larger quantity of fertilizer required on these soils and the increased relative financial burden for this input. The financial importance of fertilizer within this strategy also served to reduce the relative importance of all other inputs. Labor and land were secondary to fertilizer in terms of their cost effects. Increases of 10% to either input would change product cost by about 2.5%, with labor slightly more important than land. Changes in capital input prices were least important, with a 10% change affecting product cost by 0.6% on either site.

Irrigation was not only an expensive strategy but one that was also capital intensive. Much of its added cost originated from the capital items used in the water collection and distribution systems. As such, a 10% change in the cost of this equipment would cause a 4.4% change in product cost on the Basher site and a 5.0% change on the Morrison site. The increased impact on Morrison was due to the higher irrigation cost for its well system. It should be noted that the changes to product cost in the irrigation strategy

Table 3-9. Percentage impact of 10% cost changes in basic inputs and 10% change in biomass output upon the total production cost for biomass.

Site	Management Strategy	First Rotation Product Cost $/ODt	% Change in Biomass Production Cost resulting from 10% Cost Change					% Change in Biomass Production Cost from a 10% Change to Output
			Capital	Fertilizer	Fuel	Labor	Land	
Basher	Control	28.71	0.70	0.03	0.34	3.72	3.59	11.11 for 10% decrease of output
	Irrigation	96.40	4.42	0.01	0.28	3.61	1.16	
	Fertilization	35.60	0.65	3.03	0.27	2.56	2.41	0.09 for 10% increase of output
	Fertilization/ Irrigation	84.71	3.89	1.26	0.26	3.15	1.00	
Morrison	Control	32.12	0.70	0.03	0.34	3.72	3.59	11.11 for 10% decrease of output
	Irrigation	103.62	5.03	0.01	0.32	3.14	1.04	
	Fertilization	44.10	0.58	4.92	0.24	2.30	2.16	0.09 for 10% increase of output
	Fertilization/ Irrigation	101.86	4.29	1.98	0.28	2.66	0.87	

also represented the largest absolute cost changes among all strategies due to the high cost for the basic strategy - $96.40/ODt for Basher and $103.62/ODt for Morrison.

Labor was the second most important item from a costing standpoint in the irrigation strategy. Changes of 10% to labor imposed a 3.6% change to biomass production cost at Basher and a 3.1% change at Morrison. Because the irrigation strategy required the most labor, a change in labor cost imparted a greater absolute cost change per ODt for irrigation than all other management stragegies. Land was of tertiary financial importance to the irrigation strategy, with a 10% cost change in land imposing a 1% change on product cost.

The combined fertilization/irrigation strategy was dominated by the capital inputs of irrigation. Changes to capital costs of 10% impacted on total product cost by 3.9% on Basher and by 4.3% on Morrison. Labor was the secondary financial input. Cost changes to labor at 10% imparted a 3.1% change to total product cost on Basher and 2.7% on Morrison. Fertilizer was of tertiary financial importance, with a 10% cost change affecting total product cost by 1.3% on Basher and 2.0% on Morrison. The larger impact on Morrison was due to more fertilizer being used on this site. A cost of 10% to land affected total product cost by about 1%.

A 10% change to biomass yield had a greater impact on total biomass production cost than any of the 10% changes to individual biomass production cost inputs. The biomass production cost ($/ODt) was determined from the division of total production cost ($/ha) by total biomass yield (ODt/ha). As such, a 10% increase to the denominator had the effect of reducing the average by an amount of 1/1.1 or 90.9% of the former value (i.e., a 9.1% decrease). The reciprocal move of decreasing output by 10% affected the average by 1/.9 or 111.1% (i.e., an 11.1% increase).

Biomass Production Financial Sensitivity Analysis Summary - Overall, the cost changes reflected the relative financial impact of the principle inputs within the various management strategies. For control, labor and land were the primary inputs. The addition of fertilizer shifted primary attention to this input from a costing standpoint, with labor and land becoming secondary. Capital and labor were the controlling features in an irrigation budget. The fertilization/irrigation strategy was still dominated by capital, with labor second and fertilizer third. Fuel, as an input, had only a minor effect within any of the management strategy/site combinations.

The 10% change in biomass yields for the various management strategy/site combinations had a greater impact on biomass production costs than did any of the 10% changes to input costs. This was due to the change affecting the central output feature of each production function rather than just one of several inputs. Furthermore, the percentage effect of the output change was constant among all strategy/site combinations due to the mathematical configuration of this change.

Biomass Production Energy Sensitivity Analysis - A detailed energy sensitivity analysis comparable to the financial sensitivity analysis was not implemented. A change in capital would not be applicable in energy

terms. A ±10% change in the energy inputs of fertilization, fuel, labor or land could occur due to: 1) variations in the actual values as calculated (for example the energy embodied in materials), 2) different technological approaches in organizing and manufacturing these inputs (in the cases of fertilizer and fuel) and/or 3) changes in the amount of input used in the biomass production function. Since energy is a physical measurement compared to a financial cost, it would be more difficult in an operational sense to vary energy costs than financial costs. Land energy costs dominated the supply system resulting in minimal effects from changes in the energy costs of fertilizers, fuel or labor. Similar to the financial cost sensitivity analysis, changes in the biomass yield appeared to have the most influence on energy cost structure. However, land had nearly as large an impact as biomass yield on the total biomass production energy cost.

Conversion Product Sensitivity Analysis - The impact of a 10% change in total biomass production costs on final product (electricity or ethanol) costs was also evaluated for each management strategy. Technical and cost characteristics of the harvesting, transportation and conversion strategies were held constant.

Table 3-10 lists the percent change in electricity and ethanol costs ($/kwh or $/ℓ) for an increase or decrease in total biomass production costs ($/ODt). It should be noted that a 10% decrease in the production costs still produced a loss for the conversion of SRIC biomass to electricity and ethanol. A ten percent change in production costs changed the electricity costs by about 2% for control and fertilization and 4% for irrigation and fertilization/irrigation. In like manner, a ten percent change in production costs changed the ethanol costs by about 3% for control, 4% for fertilization and 6% for irrigation and fertilization/irrigation. Therefore, changes in production costs influenced ethanol costs more than electricity costs.

Another approach to analyzing the impact of biomass production costs on electricity and ethanol costs is to determine the percent reduction in production costs necessary to meet the current selling price of the product (Table 3-11). Since the biomass production costs ($/kwh) for the first rotation alone exceeded the current selling price for electricity, the production costs would have to be dramatically modified to obtain reasonable costs per kwh. However, it was possible to conduct a breakeven analysis for ethanol.

If the production costs were reduced by about 30-50%, the control and fertilization strategies appeared to breakeven. An alternative to reducing the production costs is to increase the biomass output for a given cost (Table 3-11). The result would be the same as increasing ethanol conversion efficiency. A 20 to 50% increase in biomass yield produced breakeven ethanol prices for the control and fertilization strategies. Increases in biomass yield from coppice growth, management and genetic gains, combined with more efficient biomass to ethanol conversion technology, may approach a breakeven situation.

Sensitivity of the final product energy costs was hampered by the lack of quality energy estimates related to wood conversion plant costs in the literature. Hence, the influence of production energy cost changes on the product costs was not analyzed.

Table 3-10. Percentage impact of 10% change in biomass production cost upon the financial and energy costs of producing electricity and ethanol.

Site	Management Strategy	Electricity Financial Costs: Cost $/kwh	Electricity: % Change in Product Cost -10%	Electricity: % Change in Product Cost +10%	Ethanol Financial Costs: Input Cost $/ℓ	Ethanol: % Change in Product Cost -10%	Ethanol: % Change in Product Cost +10%
Basher	Control	0.118	-1.69	1.69	0.49	-2.04	4.08
	Irrigation	0.162	-4.32	3.70	0.85	-5.88	5.88
	Fertilization	0.122	-1.64	2.46	0.53	-3.77	3.77
	Fertilization/ Irrigation	0.155	-3.87	3.23	0.79	-6.33	3.80
Morrison	Control	0.119	-1.68	1.68	0.51	-3.92	3.92
	Irrigation	0.166	-4.22	4.22	0.89	-6.74	5.62
	Fertilization	0.128	-2.34	1.56	0.57	-3.51	5.26
	Fertilization/ Irrigation	0.166	-3.61	4.22	0.88	-6.82	5.68

Table 3-11. Ethanol financial breakeven analysis[1/].

Site	Management Strategy	Necessary Percent Reduction in Biomass Production Costs	Necessary Percent Increase in Biomass Yield or EtOH Output to Benzene[2/]
Basher	Control	28	20
	Irrigation	78	190
	Fertilization	40	40
	Fertilization/ Irrigation	75	160
Morrison	Control	35	30
	Irrigation	80	210
	Fertilization	55	50
	Fertilization/ Irrigation	80	200

[1/] To have an input cost of Z0.45/ℓ of EtOH.

[2/] An increase in biomass yield for a given ethanol conversion efficency has the same effect as increasing the ethanol conversion efficency for a given biomass yield.

SUMMARY

This project was divided into two general, but related, areas. The purpose of the first overall area was to determine growth characteristics and biomass yields for a Populus hybrid grown under four management strategies on two dissimilar sites. The purpose of the second overall area was to expand the biomass production data into complete net financial and energy analyses. In order to complete these objectives, biomass production data were combined with certain laboratory data to predict potential conversion products for use in economic modeling. This project incorporated the culturing and managerial aspects of biomass production with the utilization characteristics of the material and evaluated the complete system through a financial and energy framework.

The financial and energy analyses in this project were based on a self-owned, fully integrated commercial-scale operation. Costs for nursery stock, establishment and cultural maintenance operations were developed from field data obtained in this project, and combined with operational information in the literature supplemented by consultations with agricultural engineers and professional farm managers. These production costs were coupled with harvest, transportation, storage and conversion costs obtained from the literature for use in analyzing the commercial-scale operation from production through conversion.

The financial and energy analyses for this project contrasted the inputs for producing, harvesting, transporting and processing biomass against the potentially recoverable outputs from the forest biomass. Comparisons of the financial and energy analyses established the relative importance of the constraints within the economic model and the sensitivity of various inputs within the overall energy recovery systems. Linear programming analyzed the complete system and compared selected management and conversion strategies.

Experimental Design - Populus hybrid SRIC plantations were established under four management strategies (control, fertilization, irrigation and fertilization/irrigation) on two sites representing favorable (Basher silt loam soil) and unfavorable (Morrison sandy loam soil) inherent growth conditions. Each plantation site (1.2 ha) consisted of six replications (0.2 ha each) with three replications planted in 1980 and three replications planted in 1981. Each replication included four treatment units (0.05 ha each for control, fertilization, irrigation and fertilization/irrigation). Growing space for Populus hybrid NE-388 cuttings was 0.48 m^2 with 0.8 m between rows and 0.6 m between trees in the rows. In each treatment unit, trees were designated for both continuous inventory and annual destructive sampling over a four year period.

A fertilization schedule based on attaining a corn silage yield of 47 tonne/ha was applied to the appropriate treatment units of the 1980 and 1981 plantations. Chemical weed control was implemented in 1981 on 1980 and 1981 planted trees. A trickle irrigation system was installed at each site in 1981 to reduce growth loss from moisture stress by maintaining soil moisture above the 50% available water level.

Procedures - Biomass survival rates, yields and growth rates were determined as a function of management strategy, age and site. Nutrient depletion as a function of management strategy, age and site was gauged through annual determination of nutrient concentrations of wood, bark, wood/bark composite, foliar, litter, corn and soil specimens. Sample trees harvested at the end of the growing season were also analyzed for: 1) specific gravity (maximum moisture content method), 2) moisture content (ASTM D-2016), 3) gross heat of combustion (ASTM D-2015), 4) ash content (ASTM D-1102), 5) nutrient content (N, P, K, Ca and Mg), 6) extractive content (ASTM D-1105), 7) holocellulose content (acid chlorite method), 8) alpha cellulose content (ASTM D-1103) and 9) Klason lignin content (ASTM D-1106) of wood, bark and composite wood/bark specimens as a function of management strategy, age and site.

Financial and energy inputs required to establish and maintain short-rotation plantations were determined. Linear programming was used to: 1) analyze net financial and energy analyses, 2) recommend an optimal management strategy for each conversion strategy and 3) analyze sensitivity of the financial and energy outputs from each conversion strategy with respect to various financial and energy inputs.

All production/harvesting/conversion operations costs were analyzed on a financial and energy basis. Costs were divided into variable and fixed expenses.

Variable costs for an operation included labor, fuel, materials and maintenance of the equipment. Base pay rates were taken from Doane's (1981) with 5 to 20% added for fringe benefits. Fixed costs included insurance, equipment shelter, depreciation and interest.

Site Preparation and Weed Control - The only weed control measures in the plantation treatment units established in 1980 were plowing and disking prior to planting. Native herbaceous plant growth was about 300 ODg/m^2 at the more favorable (Basher) site and about 200 ODg/m^2 at the less favorable (Morrison) site in 1980 when no herbicides were used. Chemical weed control was implemented in 1981. Herbicide treatments reduced the 1981 herbaceous plant growth by 77% and 84% at the Basher and Morrison sites, respectively. This difference in establishment year weed control was an additional factor in the experimental design.

Compared to the poor weed control for the 1980 planted trees, the effective weed control program for the 1981 planted trees increased the height and diameter of trees at both sites for every age and management strategy (except three year old Basher fertilized height). Weed control measures had the greatest effect on the control treatment and the least effect on the fertilization and fertilization/irrigation treatments.

Management Strategy Effects - Fertilization did not have an effect on survival in the establishment year. However, fertilization of the 1980 planted trees (poor weed control) produced greater height and diameter values than non-fertilized trees, and similar first season height and diameter values for the 1981 planted trees (good weed control). This reflects the depression in control treatment growth caused by weed competition. Neither irrigation nor the combined fertilization/irrigation

treatment markedly influenced survival rate, height or diameter during the establishment phase. This suggests that native site fertility and normal rainfall were adequate for tree survival, total height and diameter growth in the establishment phase given similar weather, planting dates, weed control, site, tree parentage and spacing conditions.

Fertilization - Survival rates of fertilized trees were somewhat lower than control trees for each planting year-site combination except 1981 Basher. At the end of the first rotation, fertilization of the 1980 planted trees at both sites increased average total height and stem diameter values by about 30% over the control treatment. The greatest height and diameter differentials between fertilized and nonfertilized trees occurred during the first two growing seasons, the period when weed competition was most intense.

In the first three years fertilization of the 1981 planted trees produced average height and diameter growth rates similar to the control growth rates. In the fourth growing season, averaging over both sites, the fertilized trees were 30% and 45% greater in height and diameter, respectively, than control trees. Fertilization of 1981 planted trees resulted in a net height and diameter increase of 5% and 12%, respectively, over control trees.

Irrigation - Survival rates of 1980 and 1981 planted irrigation and control trees were about equal on the Basher site. On the Morrison site, survival rates of 1980 and 1981 planted irrigation trees were somewhat less than controls.

Irrigation in the second, third and fourth growing seasons established with poor weed control (1980 planting) resulted in about a 12% increase in the four year old tree size values over the control treatment. In contrast, four years of irrigation to trees established with good weed control (1981 planting) had no apparent first rotation benefit. Averaged over both sites, irrigated trees planted in 1980 and 1981 were substantially smaller in height and diameter than fertilization and fertilization/irrigation trees.

Fertilization/Irrigation - The absolute and relative tree growth variables for the fertilization/irrigation treatment were dependent on weed control efficiency in the establishment year. For the 1980 plantings, fertilization/irrigation resulted in trees which annually were taller and larger in diameter than either the control or irrigated trees. When compared to the control treatment averages, fertilization/irrigation treatment units averaged about 30% greater in the four year total height and about 45% greater in the four year stem diameter. Fertilization/irrigation of the 1980 planted trees did not result in an average tree size advantage over the fertilized tree values. The 1981 planted fertilization/irrigation trees had significantly greater two, three and four year old average total height and stem diameter values than the control, irrigation and fertilization treatments. However, the differences in the 1981 planted trees between the fertilization/irrigation and the control or the irrigation treatments were not as large as with the 1980 plantings. After four growing seasons, the 1981 planted fertilization/irrigation trees

averaged about 10% greater in total height and 15% greater in stem diameter, as compared to the control trees.

Growth - First rotation *Populus* hybrid growth demonstrated:

(1) Weed control in the establishment year had a significant effect on height and diameter of trees and on growth response to fertilization and irrigation amendments throughout the first rotation.

(2) Two year old trees grew faster than one year old trees, two year growth rates were sustained in the third year but slowed in the fourth year.

(3) Favorable sites (Basher) resulted in trees that were somewhat larger compared to unfavorable sites (Morrison).

(4) Fertilization and fertilization/irrigation investments increased tree growth over no amendments. Irrigation had mixed results.

Yield - Four year old total tree biomass yields from 1980 planted trees averaged 21.4, 26.9, 33.1 and 37.0 ODt/ha for control, irrigation, fertilization and fertilization/irrigation strategies, respectively. The irrigation, fertilization and fertilization/irrigation amendments resulted in additional yields of 26%, 55% and 73%, respectively, over control yields. The 1980 planted tree yields were not used for the economic analyses because of ineffective weed control measures in the establishment year. Four year old total tree biomass yield from 1981 planted trees (good weed control) averaged 33.5, 33.3, 40.4 and 42.1 ODt/ha for control, irrigation, fertilization and fertilization/irrigation treatments, respectively.

Annual yield of hybrid poplar biomass (including weight of leaves) averaged 11.3 ODt/ha and 13.1 ODt/ha for the control and fertilization strategies, respectively, over the first rotation. Natural vegetation produced annual yields of 3.3 ODt/ha.

The fertilized annual woody biomass yield of 13.1 ODt/ha is in contrast with an average annual yield of 16.9 ODt/ha of corn. It is anticipated that subsequent rotations of hybrid poplar may reduce or eliminate this yield differential.

Oven dry total tree and component *Populus* hybrid yields revealed that:

(1) Proper weed control substantially increased biomass yields.

(2) Biomass productivity increased more in the second year compared to the first year, was greater in the third year than the second year and similar in the third and fourth years.

(3) Favorable sites yielded slightly more biomass, in the same time frame, compared to unfavorable sites.

(4) Irrigation, fertilization and fertilization/irrigation increased two, three and four year old biomass production.

(5) The increased yield realized through the addition of cultural amendments was an increase primarily in stemwood as opposed to bark or branchwood.

Soil Fertility - Analysis of nutrient concentrations in the Ap and upper 15 cm of the B soil horizons showed that soil fertility increased over the four years of the first rotation for all treatment units. The supply capacity of the soil plus the decomposition and mineralization of litter fall possibly exceeded the nutrient uptake of the trees in the first rotation.

Physical and Chemical Properties - The energy and chemical contents of the biomass components influence the conversion products. Specific gravity, moisture content, gross heat of combustion, ash, and extractive, holocellulose, Klason lignin and alpha cellulose content values were determined for wood, bark and wood/bark composite specimens as a function of management strategy, age and site. General trends were:

(1) Most physical and chemical properties did not vary significantly with site at the 0.05 level except for ash and extractive content. There were statistically significant differences in properties among management strategies. However, these differences did not necessarily exhibit consistent trends.

(2) Variations in properties between successive ages appear to decrease with time.

(3) Wood specimens have higher specific gravity, holocellulose and alpha cellulose values than bark.

(4) Bark has higher gross heat of combustion, ash content and extractive content values than wood.

(5) Wood and bark have comparable moisture and Klason lignin contents.

Financial and Energy Analyses - The financial and energy analyses for this project balance the inputs for producing, harvesting, transporting and processing against the recoverable energy from the forest biomass. The LP basis for analyzing the biomass system characterized the production function (e.g., fertilizer, irrigation amendments, etc.) and related inputs (e.g., harvesting, transportation, etc.) to outputs (e.g., financial and energy gains). All of the data were entered into the problem as alternative strategies for growing biomass and converting the material to energy. The solution to this problem represented a selection of the most efficient strategies for attaining a maximum net financial and energy output from the system.

The overall LP design compartmentalized the functions into separate units. These units followed the sequential order: 1) biomass production, 2) harvesting, transportation, 3) storage and 4) conversion of biomass to energy.

The model also identified biological, physical, financial cost, energy and time constraints within each function and prioritized these constraints among functions. This procedure identified the influence each function had on the other functions.

Biomass Production - Equipment size and operational time were major constraints in the establishment phase. Plantation establishment included the establishment and operation of a nursery as a variable cost of the planting operation. Operations for nursery establishment were the same as for plantation establishment.

Planting was the most expensive establishment operational cost at either site, at $.5 \times 10^6$ kcal/ha and $192/ha, accounting for about 73% of all establishment operation financial and energy costs. Of the two cultural amendments, fertilization was high in energy costs while irrigation was high in financial costs.

Property rental and taxes during the four year rotation, at 44×10^6 kcal/ha and $298/ha, were the most expensive maintenance costs, accounting for 98% and 52% of all maintenance operation financial and energy costs, respectively. As in the establishment phase, of the two cultural amendments, fertilization was the higher energy cost on both sites, at about 14×10^6 kcal/ha and accounting for about 72% of the total. Irrigation was the higher financial cost on both sites averaging about $1900/ha and accounting for about 80% of the total.

Land costs were a major component of the establishment and production costs of SRIC biomass. It is important to note that the magnitude of these constraints may influence certain silvicultural considerations.

The total production costs by management strategy for the first four year rotation ranged from $1,014.61/ha for the control strategy on both Basher and Morrison sites to $4,187.61/ha for the fertilization/irrigation strategy on the Morrison site. The least expensive strategy was the control option on the Basher site ($28.71/ODt and 1.302×10^6 kcal/ODt) and on the Morrison site ($32.12/ODt and 1.456×10^6 kcal/ODt). Fertilization increased financial costs per ODt by about 24% and 37% on the Basher and Morrison sites, respectively, and increased output over control by about 20% at either site. Energy costs per ODt were increased by fertilization by about 5% and 10% at the Basher and Morrison sites, respectively. Irrigation and fertilization/irrigation increased both financial and energy unit costs well beyond the associated increased outputs.

Harvest, Transportation and Storage - Analysis of the harvest and transport of the biomass was approached through a comparison of two distinct strategies: harvest/baling and harvest/chipping. In the harvest/baling strategy trees were cut, crushed and permitted to dry in the field before being loaded and transported to the storage/conversion site. The second scenario involved in-field chipping following harvest and the transport of chips to a storage/conversion site. The cost of the harvest-transport function per oven dry tonne was not significantly different among the individual management strategy/site combinations. The efficiency of both harvest systems was assumed to be 90%; i.e., 10% by weight of fiber would be lost during processing.

The method of storage and drying of biomass at the conversion site was dependent on the form of the material as it arrived at the site and its subsequent processing specifications. For example, in the production of ethanol, moisture content is controlled at the beginning of the conversion process. However, moisture content should be below 25% for direct incineration, pyrolysis or liquefaction for efficient process control.

Several patterns of harvest, transportation, drying and storage strategies were examined. For fermentation (i.e., ethanol production), the harvest/baling-wet storage strategy was recommended as the most cost efficient pattern. For direct incineration more cost efficient patterns were: 1) harvest/baling-chip, dry storage, dry, 2) harvest/chipping-dry storage, dry and 3) harvest/chipping-dry, dry indoor storage. The recommended pattern for ethanol production was financially least expensive but was the most expensive pattern in terms of energy. For end uses requiring dry feedstock, the pattern involving harvest/baling-chip, dry storage was the least expensive on both the financial and energy bases.

Conversion - SRIC biomass can represent the production of a dedicated feedstock, more homogeneous in nature than conventional woody biomass, for conversion to a high grade energy or secondary fuel product. Conversion strategies examined the four year old biomass yield per hectare from first rotation hybrid poplar by site and treatment, associated gross heat of combustion and usable heat content values and ethanol recovery yields. The production of electricity was estimated from the usable heat content and known power plant efficiency, and ethanol yields were estimated using present recovery processes.

Net financial and energy analyses using forest biomass from the four management strategies in the conversion to electricity or ethanol identified modest to major limitations. Production of electricity from SRIC biomass had major cost limitations. However, the financial analysis of converting SRIC biomass to ethanol provided results that may become more favorable in the future.

Economic analyses of the SRIC production data identified control, followed by fertilization, as the most reasonable cultural management strategy to pursue. Additional improvements in SRIC biomass yields, reduction in costs per unit weight and increases in conversion yields will improve the potential for SRIC biomass to be converted to energy.

Sensitivity - Sensitivity analyses were conducted for each site/management strategy combination to determine: 1) the sensitivity of total biomass production cost to variations of ±10% in individual input costs ($/ODt) and biomass yield (ODt/ha) and 2) the sensitivity of final product (ethanol and electricity) cost to variations of ±10% in total biomass production cost and biomass yield. Individual input costs within the production function examined were capital, fertilization, fuel, labor and land.

Within the control strategy, labor and land cost inputs had the greatest impact on total biomass production cost. Fertilization, labor and land, in decreasing order, were the most influential input costs in the fertilization strategy. Capital, then labor, influenced total biomass production cost more than other inputs for both the irrigation and

fertilization/irrigation strategies. Fertilization was the third most important input cost in the fertilization/irrigation strategy. Fuel was a relatively minor input cost in all cases. A 10% change in biomass yield affected total biomass production cost by 9-11% while the greatest impact from a change in any individual input cost was only 5% (fertilization in the Morrison/fertilization strategy). This was due to the change affecting the central output feature of the production function rather than just one of several inputs.

A 10% change in total biomass production cost ($/ODt) would produce a 2-4% change in the cost of electricity ($/kwh) or a 2-7% change in the cost of ethanol ($/ℓ). Even with a 10% decrease in biomass production cost, the net cost of producing electricity or ethanol from SRIC biomass would still be negative.

The increases in biomass yield and/or biomass conversion efficiencies necessary to breakeven appear to be lower for ethanol production than for electrical generation. It should be noted that electricity and ethanol were chosen as final products for analysis and comparison purposes, but other conversion products may become more attractive with changes in technology and the market place.

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APPENDIX A

TASK 1

ESTABLISH PLANTATION

Table A-1 Species of grass-and-grasslike and broadleaf weeds that collectively accounted for 90% or more of the herbaceous vegetation growing on 25.0 m^2 permanent sample plots adjacent to the study plantations.

Species	Number of years since site preparation			
	One[1/]		Two[2/]	
	Basher	Morrison	Basher	Morrison
Grass-and-grasslike				
crab grass (*Digitaria sanguinalis* L)	X	X	X	
Kentucky bluegrass (*Poa pratensis* L.)		X	X	X
panicum	X	X		X
timothy (*Phleum pratense* L.)		X	X	X
wild garlic (*Allium oleraceum* L.)		X		
yellow foxtail (*Setaria lutescens*) Weigel Hubb.	X			X
yellow nutsedge (*Cyperus esculentus* L.)	X			
Broadleaf weeds				
asters (*Aster spp.*)		X		X
broad dock (*Rumex* obtusifolius L.)			X	
clovers (*Trifolium* spp)	X	X	X	X
daisy fleabane (*Erigeron strigosus* Muhl.)	X			X
goldenrods (*Solidago* spp)		X	X	X
horse nettle (*Solanum carolinense* L.)	X		X	X
lance-leaf plantain (*Plantago lanceolata* L.)		X		X
Queen Annes lace (*Daucus carota* L.)		X	X	X
pale plantain (*Plantago rugelii* Decne.)	X		X	
peppergrass (*Lepidium virginicum* L.)		X		X
ragweed (*Ambrosia artemisiifolia* L.)	X	X		X
smartweed, common (*Polygonum persicaria* L.)	X			
yellow wood sorrel (*Oxalis europaea* L.)	X		X	

1/ Site preparation included a total kill herbicide in August-September 1980, tilled in October 1980, disked in April 1981. No other weed control was employed.

2/ Site preparation included plowing and disking in April 1980. No other weed control was employed.

Table A-2. Average[1,2/] oven dry weights of grass (and grasslike), broadleaf weeds and total herbaceous vegetation[3/] measured at the end of the growing season (September) on the 1981 planted replications, by plantation site and treatment.

Plantation Site/ Treatment	Grass	Broadleaf Weeds	Total
	g/m^2		
Basher			
Control	25.4 b	30.0 ab	55.4 ab
Irrigation	22.6 b	50.4 a	72.9 ab
Fertilization	21.5 b	17.3 b	40.5 c
Fertilization/ Irrigation	65.3 a	20.9 b	86.1 a
Average	33.7 x	29.6 x	63.7 x
Morrison			
Control	1.5 c	22.4 b	23.9 c
Irrigation	5.2 c	20.2 b	25.4 c
Fertilization	4.2 c	34.8 ab	38.9 c
Fertilization/ Irrigation	2.0 c	29.1 ab	31.1 c
Average	3.2 y	26.6 x	29.8 y

1/ Each value is an average of twelve 1.0 m^2 plots.

2/ Means followed by the same letter are not significantly different at the 0.05 level.

3/ See Table A-1 for a listing of weed species in each group.

Table A-3. Average[1/] analysis of soil collected[2/] prior to the 1980 and 1981 growing season from the Ap horizon (0-20 cm) and the upper 15 cm of the B horizon.

Plantation Site	Horizon	pH	P	K	Mg	Ca	CEC	K	Mg	Ca
		Test Results								
		kg/ha	(- - -		meq/100g	- - -)		(% saturation)		
1980 Replication										
Basher	Ap	6.1	29.	0.10	0.7	3.3	7.7	1.3	8.5	44.1
	upper B	6.6	12.	0.06	0.7	3.2	6.0	1.0	10.5	53.3
Morrison	Ap	5.5	26.	0.07	0.3	2.1	9.0	.8	3.5	25.1
	upper B	5.9	11.	0.06	0.4	3.5	7.8	.9	4.8	44.6
1981 Replication										
Basher	Ap	6.0	64.	0.17	0.7	3.8	9.8	1.8	6.7	38.5
	upper B	6.2	45.	0.12	0.6	3.2	7.5	1.5	10.3	41.6
Morrison	Ap	6.0	44.	0.14	0.4	4.0	8.6	1.7	5.1	46.9
	upper B	5.7	43.	0.19	0.3	3.1	9.4	1.9	4.0	33.3

1/ An average of four samples with each sample being a composite of 8 soil plugs.

2/ The areas sampled were those to be planted in the 1980 and 1981 growing season.

Table A-4. First growing season average survival[1,2/] by plantation site, treatment and measurement date for the 1980 planted trees.

Plantation Site Treatment	% Survival at Measurement Date							
	July 3	July 11	July 18	July 28	Aug 7	Aug 19	Sept 5	Sept 29
	%							
Basher								
Control	96	90	94	98	96	90	96	78
Irrigation[3/]	90	84	100	96	98	98	98	76
Fertilization	86	86	94	80	86	92	88	78
Fertilization/Irrigation[3/]	90	88	92	88	73	86	88	82
Average	90	87	95	90	88	91	92	78
Morrison								
Control	92	88	86	90	80	82	84	80
Irrigation[3/]	88	96	86	92	94	92	88	84
Fertilization	88	94	94	86	92	80	82	80
Fertilization/Irrigation[3/]	84	88	94	84	84	76	80	82
Average	88	91	90	88	87	82	83	81

1/ Each value is based on 51 completely independent tree observations per site per treatment.

2/ Trees less than 0.1 meter tall were considered dead.

3/ Although designed for irrigation, no water was applied in the 1980 growing season.

Table A-5. First growing season average survival[1,2/] by plantation site, treatment and measurement date for the 1981 planted trees.

Plantation Site Treatment	% Survival at Measurement Date							
	June 19	July 2	July 17	July 31	Aug 14	Aug 28	Sept 10	Sept 29
	%							
Basher								
Control	86	84	96	94	96	92	96	88
Irrigation	92	80	84	94	86	98	96	96
Fertilization	90	98	98	96	94	96	98	95
Fertilization/ Irrigation	92	92	90	94	96	88	94	96
Average	90	88	92	95	93	94	96	94
Morrison								
Control	94	92	98	82	90	90	90	94
Irrigation	74	92	88	78	90	86	94	86
Fertilization	76	76	69	80	96	90	78	82
Fertilization/ Irrigation	78	78	86	92	80	88	76	82
Average	80	84	85	83	89	89	84	86

1/ Each value is based on 51 completely independent tree observations per site per treatment.

2/ Trees less than 0.1 meter tall were considered dead.

Table A-6. First growing season average[1,2/] total height by plantation site, treatment and measurement date for the 1980 planted trees.

Plantation Site Treatment	Total Height at Measurement Date							
	July 3	July 11	July 18	July 28	Aug 7	Aug 19	Sept 5	Sept 29
	meters							
Basher								
Control	0.31 ab	0.34 ab	0.35 bc	0.49 ab	0.43 b	0.49 c	0.71 de	0.68 d
Irrigation[3/]	0.26 b	0.30 bc	0.33 c	0.46 b	0.50 ab	0.52 cc	0.78 cde	0.86 cd
Fertilization	0.32 a	0.30 bc	0.44 a	0.47 b	0.41 b	0.70 a	0.99 ab	0.96 bc
Fertilization/ Irrigation	0.29 ab	0.28 c	0.39 abc	0.49 ab	0.61 a	0.65 ab	0.92 abc	1.13 ab
Average	0.30	0.31	0.38	0.48	0.49	0.59	0.85	0.91
Morrison								
Control	0.27 b	0.38 a	0.32 c	0.58 a	0.51 ab	0.54 bc	0.82 bcd	0.86 cd
Irrigation[3/]	0.29 ab	0.36 a	0.42 ab	0.53 ab	0.50 ab	0.64 ab	0.60 e	0.70 d
Fertilization	0.27 b	0.34 ab	0.40 ab	0.50 ab	0.55 a	0.66 ab	1.00 ab	1.20 a
Fertilization/ Irrigation	0.31 ab	0.33 abc	0.37 abc	0.43 b	0.40 b	0.70 a	1.03 a	1.21 a
Average	0.28	0.35	0.38	0.51	0.49	0.64	0.86	0.99

1/ Each value is from 30 completely independent observations.

2/ Treatment means within and between plantation sites with common letter are not significantly different at the .05 level for each date. Statistical mean separations were evaluated by the Duncan method on the Site X Treatment factor from analysis of variance. Site means (N=120) were not significantly different (0.05 level) for all measurement dates, except July 11 and September 29.

3/ Although designed for irrigation, no water was applied in the 1980 growing season.

Table A-7. First growing season average[1,2/] total height by plantation site, treatment and measurement date for the 1981 planted trees.

Plantation Site Treatment	Total Height at Measurement Date							
	June 19	July 2	July 17	July 31	Aug 14	Aug 28	Sept 10	Sept 29
	meters							
Basher								
Control	0.28 a	0.33 cd	0.56 ab	0.80 abc	1.23 ab	1.56 bc	1.66 ab	1.56 bc
Irrigation	0.23 bcd	0.36 bcd	0.59 ab	0.76 abc	1.27 ab	1.43 bcd	1.70 ab	1.51 c
Fertilization	0.25 abcd	0.42 a	0.61 ab	0.92 a	1.29 ab	1.62 ab	1.78 a	1.78 ab
Fertilization/ Irrigation	0.22 cd	0.40 ab	0.61 ab	0.87 ab	1.38 a	1.75 a	1.67 ab	1.80 a
Average	0.24	0.38	0.59	0.84	1.29	1.58	1.70	1.66
Morrison								
Control	0.26 ab	0.39 ab	0.63 a	0.81 abc	1.34 a	1.31 d	1.78 a	1.62 abc
Irrigation	0.20 d	0.35 bcd	0.52 b	0.71 c	1.13 bc	1.62 ab	1.71 ab	1.52 c
Fertilization	0.22 ac	0.38 abc	0.54 ab	0.81 abc	1.40 a	1.34 d	1.54 b	1.60 abc
Fertilization/ Irrigation	0.25 abcd	0.32 d	0.57 ab	0.87 ab	1.01 c	1.40 cd	1.61 ab	1.65 abc
Average	0.23	0.36	0.57	0.80	1.22	1.41	1.66	1.60

1/ Each value is from 30 completely independent observations per site per treatment.

2/ Treatment means within and between plantation sites with common letter are not significantly different at the .05 level for each date. Statistical mean separations were evaluated by the Duncan method on the Site X Treatment factor from analysis of variance. Site means (N=120) were not significnatly different (0.05 level) for all measurement dates, except August 28.

Table A-8. Average[1/] weekly maximum and minimum temperatures and rainfall for the Basher and Morrison plantation sites in 1981.

Week Starting	Weekly Maximum Temperature		Weekly Minimum Tempeature		Weekly Rainfall Temperature	
	Basher	Morrison	Basher	Morrison	Basher	Morrison
	(- - - - - - - - - - - C° - - - - - - - - - - -)				(- - - - cm - - -)	
June 1	--	22.4	--	14.7	4.83	4.83
June 8	26.3	25.3	16.1	15.9	2.29	2.29
June 15	27.8	27.3	14.9	15.9	3.66	3.54
June 22	24.0	23.9	7.9	8.5	2.29	2.16
June 29	26.5	24.6	15.5	15.0	0.28	0.36
July 6	30.6	30.9	15.3	16.4	0.00	0.00
July 13	28.4	28.0	13.4	13.9	0.00	0.00
July 20	24.5	24.3	15.5	15.6	6.30	6.35
July 27	25.9	25.5	12.0	12.3	1.55	1.24
Aug 3	27.2	27.3	14.8	15.4	0.00	0.00
Aug 10	27.1	27.0	13.5	14.1	0.71	0.46
Aug 17	26.1	26.1	5.9	6.8	0.00	0.00
Ayg 24	26.9	26.8	12.4	13.0	0.00	0.00
Aug 31	20.8	21.0	17.5	18.2	4.19	3.91
Sept 7	25.0	25.3	11.2	13.0	2.92	2.92

[1/] From daily maximum and minimum values as measured by a hydrothermograph at each site.

Table A-9. Average[1/] soil moisture characteristics in the upper 20 cm of the units to be irrigated at the Basher plantation site, by treatment and tree ages.

Tree age	Treatment	Rep	Bulk[2/] Density of Dry Soil	Available Water[3/] Amount 100	75	50	Oven dry 100	Moisture 75	Control 50
			(kg/m^3)	--- kg/m^3 ----			-------- % --------		
One year old									
	Irrigation	4	1482	301	255	208	20.3	17.2	14.1
		5	1514	346	269	232	22.9	17.8	15.3
		6	1442	314	264	213	21.8	18.3	14.8
	Fertilization/ Irrigation	4	1492	368	312	242	24.7	20.9	16.2
		5	1655	282	243	205	17.0	14.7	12.4
		6	1338	380	312	242	28.4	23.3	18.1
Two year old									
	Irrigation	1	1527	320	271	219	21.0	17.7	14.4
		2	1495	320	270	218	21.4	18.1	14.6
		3	1516	296	253	207	19.5	16.6	13.6
	Fertilization/ Irrigation	1	1569	269	232	195	17.2	14.8	12.5
		2	1436	333	277	221	23.2	19.3	15.4
		3	1471	341	285	227	23.2	19.4	15.5

[1/] Average of three sample points per unit.

[2/] Field measured.

[3/] Available H_2O was based on field measurements of field capacity and reported level of minimum available H_2O (15 atm) for Ap horizons of Basher soil which was 7.8% moisture content on an oven dry basis. Field capacity was 100%, 15 atm was 0% available H_2O.

Table A-10. Average[1/] soil moisture characteristics in the upper 20 cm of the units to be irrigated at the Morrison plantation site, by treatment and tree ages.

Tree age	Treatment	Rep	Bulk[2/] Density of Dry Soil	Available Water[3/] Amount 100	75	50	Oven dry 100	Moisture 75	Control 50
			(kg/m^3)	- - - kg/m^3 - - - -			- - - - - - - - % - - - - - - - -		
One year old									
	Irrigation	4	1316	327	258	189	24.8	19.6	14.4
		5	1308	285	227	168	21.8	17.4	12.9
		6	1380	321	256	189	23.3	18.6	13.7
	Fertilization/ Irrigation	4	1346	308	243	181	22.8	18.1	13.4
		5	1287	280	223	165	21.9	17.3	12.8
		6	1313	304	242	178	23.2	18.4	13.5
Two year old									
	Irrigation	1	1420	279	223	168	19.6	15.7	11.8
		2	1450	298	239	178	20.6	16.5	12.3
		3	1441	301	242	181	20.9	16.8	12.6
	Fertilization/ Irrigation	1	1500	269	219	164	17.9	14.6	10.9
		2	1396	279	223	166	20.0	16.0	11.9
		3	1386	248	200	152	17.9	14.4	11.0

1/ Average of three sample points per unit.

2/ Field measured.

3/ Available H_2O was based on field measurements of field capacity and reported level of minimum available H_2O (15 atm) for Ap horizons of Basher soil which was 7.8% moisture content on an oven dry basis. Field capacity was 100%, 15 atm was 0% available H_2O.

Table A-11. Amount of water applied[1/] in 1981 to one- and two-year-old trees planted at the Basher site, by treatment and replication.

Tree age	Treatment	Replication	Amount of Water by Irrigation Dates								
			July 18-20	Aug 5-7	Aug 12-14	Aug 18-20	Aug 21	Aug 25-26	Aug 26-27	Aug 27-28	Total[2/]
			liters/meter^2								
One year old											
	Irrigation	4	0	12.73	6.36	12.73	6.36	6.36	6.36	6.36	57.28
		5	0	12.73	6.36	12.73	6.36	6.36	6.36	6.36	57.28
		6	0	12.73	6.36	12.73	6.36	6.36	6.36	6.36	57.28
		Average[3/]	0	12.73	6.36	12.73	6.36	6.36	6.36	6.36	57.28
	Fertilization/ Irrigation	4	29.26	12.73	6.36	12.73	6.36	6.36	6.36	6.36	86.53
		5	0	13.90	6.36	12.73	6.36	6.36	6.36	6.36	58.45
		6	0	12.73	6.36	12.73	6.36	6.36	6.36	6.36	57.28
		Average[3/]	9.75	13.12	6.36	12.73	6.36	6.36	6.36	6.36	67.42
Two year old											
	Irrigation	1	29.26	12.73	6.36	12.73	6.36	6.36	6.36	6.36	86.53
		2	29.26	12.73	6.36	12.73	6.36	6.36	6.36	6.36	86.53
		3	29.26	14.55	6.36	12.73	6.36	6.36	6.36	6.36	88.36
		Average[3/]	29.26	13.34	6.36	12.73	6.36	6.36	6.36	6.36	87.14
	Fertilization/ Irrigation	1	29.26	12.73	6.36	25.46	6.36	6.36	12.73	6.36	105.63
		2	29.26	12.73	6.36	6.36	6.36	6.36	6.36	6.36	80.17
		3	29.26	12.73	6.36	12.73	6.36	6.36	6.36	6.36	88.36
		Average[3/]	29.26	12.73	6.36	14.85	6.36	6.36	8.48	6.36	90.78

[1/] Amount of water added to each replication-treatment unit was determined from baseline upper 20 cm soil water characteristics (see Table 26). Amount of water in the soil was checked 24 hours after irrigation to verify the upper 20 cm of soil had sufficient water. If not, irrigation was repeated.

[2/] Determined from actual amounts added in gallons/517.44 m^2. Individual irrigations may not add to total due to rounding.

[3/] Average is only of summary value.

Table A-12. Amount of water applied[1/] in 1981 to one- and two-year-old trees planted at the Morrison site, by treatment and replication.

Tree age	Treatment	Replication	Amount of Water by Irrigation Dates August 3-5	11-12	13-14	17-18	18-20	20-21	24-25	25-26	27-28	Total[2/]
			liters/meter^2									
One year old												
	Irrigation	4	12.73	7.61	12.73	12.73	6.36	6.36	6.36	6.36	6.36	77.98
		5	12.73	6.36	12.73	12.73	6.36	6.36	6.36	6.36	6.36	76.37
		6	12.73	6.36	12.73	12.73	12.25	6.36	6.36	6.36	6.36	82.29
		Average[3/]	12.73	6.78	12.73	12.73	8.32	6.36	6.36	6.36	6.36	78.88
	Fertilization/ Irrigation	4	12.73	6.36	12.73	19.09	6.36	6.36	6.36	6.36	6.36	82.73
		5	12.73	6.36	12.73	12.73	6.36	6.36	7.10	6.36	6.36	77.10
		6	12.73	6.36	12.73	12.73	6.36	6.36	6.36	6.36	6.36	76.36
		Average[3/]	12.73	6.36	12.73	14.85	6.36	6.36	6.61	6.36	6.36	78.73
Two year old												
	Irrigation	1	18.51	6.36	12.73	6.36	6.36	6.36	6.36	6.36	6.36	75.78
		2	12.73	6.36	12.73	12.73	6.36	6.36	6.36	6.36	6.36	76.37
		3	13.20	6.36	14.23	12.73	7.83	6.36	6.36	6.36	6.36	79.81
		Average[3/]	14.81	6.36	13.23	10.61	7.03	6.36	6.36	6.36	6.36	77.32
	Fertilization/ Irrigation	1	13.79	6.36	12.73	12.73	6.36	6.36	6.36	6.36	6.36	77.43
		2	12.73	6.36	12.73	12.73	6.36	6.36	6.36	6.36	12.73	82.73
		3	12.73	6.36	12.73	12.73	15.36	6.36	6.36	6.36	12.73	91.87
		Average[3/]	13.08	6.36	12.73	12.73	9.36	6.36	6.36	6.36	10.61	84.01

[1/] Amount of water added to each replication-treatment unit was determined from baseline upper 20 cm soil water characteristics (see Table 27). Amount of water in the soil was checked 24 hours after irrigation to verify the upper 20 cm of soil had sufficient water. If not, irrigation was repeated.

[2/] Determined from actual amounts added in gallons/517.44 m^2. Individual irrigations may not add to total due to rounding.

[3/] Average is only of summary value.

Table A-13. Ranges in operating parameters and field efficiencies for equipment operations.[1/]

Implement	Range in Implement size	Typical energy, power of draft requirement	Speed of performance rate	Typical Field Efficiency (%)[3] Good	Old
Disk Harrow	10' to 21' (3.1m to 6.4m)	100 to 280 lbs/ft (1459.3 to 4086.1 n/m)	3 - 6 mph (4.8 - 9.7 km/h)	70 - 90	35 - 60
Fertilizer Spreader	broadcast - 50' (15.2m)	-	3 - 5 mph (4.8 - 8.1 km/h)	60 - 75	30 - 50
Sprayer	boom - 50' (15.2m)	-	3 - 5 mph (4.8 - 8.1 km/h)	50 - 80	25 - 53.3
Mower conditioner, cutterbar-type	7' to 16' (2.1m to 4.9m)	1.0 - 1.5 DB hp/ft 2.0 - 2.5 PTO hp/ft (3.3 - 4.9 DB hp/m) (6.6 - 8.2 PTO hp/m)	4 - 6 mph (6.4 - 9.7 km/h)	60 - 85	30 - 56.7
Offset Disk	10' to 12' (3.1m to 3.7m)	250 - 400 lbs/ft (3648.3 to 5837.3 n/m)	3 - 6 mph (4.8 - 9.7 km/h)	70 - 90	35 - 60

1/ Conversion factors; 1 inch = 2.54cm, 1 foot = .3048m, 1 psi = 6.895 kPa, 1 lb = 4.448n, 1 hp = .7457 kw, and 1 mph = 1.609 km/h.

2/ DB = drawbar and PTO = power take off.

3/ Walters and Daum (1974) list typical field efficiencies for use of farm implements on good agricultural fields. The lower value for field efficiencies were reduced by 50% and the upper by 33.3% for use of farm implements on old (abandoned) agricultural fields.

Table A-14. Implement width, field efficiency, operating speed and field capacity for plantation establishment and maintenance operations.

Implement	Width (meter)	Ave. Field Efficiency (%)	Operating Speed (km/h)	Size of Tractor (hp)	Field Capacity (ha/h)
Sprayer	15.2	53.3	8.1	70	6.48
Mower-Cutterbar	4.9	56.7	9.7	70	2.64
Offset Disk	3.7	60	9.7	170	2.10
Disk Harrow	3.7	60.0	9.7	70	2.10
Hybrid Poplar Planter	4.8	53.3	2.1	70	0.54
Fertilizer Spreader	15.2	50	8.1	70	6.07

Table A-15. Manufacturing and repair energy inputs for equipment used in plantation establishment and maintenance operations.

Implement	Weight (kg)	Embodied Energy[1/]	Fabrication Energy[2/]	Repair Energy[3/]	Total Energy	Life-time	Energy[4/] /Hour	Annual Usage	No. Units	Total Annual Fixed Energy
		- - - - - (10^3 kcal)			- - - - - - - - - - - - -	(10^3 h)	(kcal/h)	(h)		(10^3 kcal)
170 hp Tractor	9979.1	117,890	18,626	36,226	156,369	12.0	13031	1026	1	13369
70 hp Tractor	3447.3	40,727	9,889	15,018	56,523	12.0	4710	1207	2	11371
							rental:	342	2	3222
Offset disk	1587.6	24,076	3,174	8,401	30,746	2.5	12298	440	1	5411
Sprayer	498.9	7,649	827	2,576	9,526	1.5	6351	572	1	3633
Mower	1315.4	20,540	2,320	7,048	25,793	1.0	25793	350	1	9028
Disk harrow	1133.9	17,197	2,194	5,978	21,879	2.5	8751	147	3	3859
Spreader	1133.9	17,754	2,000	6,004	22,202	0.8	27753	203	3	16902
Planter	680.4	10,505	1,290	2,984	12,656	1.2	10547	342	5	18035
								Total		84830

[1/] Embodied energy is calculated by multiplying implement weight by 15,000 kcal/kg for steel, 20,500 kcal/kg for tires and 11,814 kcal/kg for tractors.

[2/] Fabrication energy is calculated by multiplying the weight of the implement by 3,494 kcal/kg for tractor, 2,061 kcal/kg for plows, offset disks and planters, 1,995 kcal/kg for disk harrows and 1,764 kcal/kg for sprayers, spreaders and mowers.

[3/] To establish the energy associated with repair parts, the sum of the embodied and fabrication energy is multiplied by 0.2967 for 170 hp tractors, 0.2474 for 70 hp tractors, 0.3083 for offset disk and disk harrow, 0.2530 for planters and mowers, 0.3040 for fertilizer spreaders and 0.3040 for sprayers.

[4/] Fixed energy costs per hour equal the sum of the embodied, fabrication and repair parts energies on a reliable life basis (0.82 times sum of embodied and fabrication energy) divided by the hours of lifetime.

Table A-16. Annual fuel consumption for plantation establishment and maintenance operations.

Implement	Number of tractors and hp	Liters/h of Diesel Fuel[1/]	Hours of Operation	Liters of Diesel Fuel per year
Fall Preparation				
Sprayer (total kill herbicide)	1- 70 hp	13.25	143	1894.75
Mower Conditioner	1- 70 hp	13.25	350	4637.50
Offset Disk	1-170 hp	32.18	440	14159.20
Spring Planting				
Disk Harrow	2- 70 hp 1-170 hp	2 @ 13.25/unit 32.18	2 @ 200/units 40	6598.20
Hybrid Poplar Planter	4- 70 hp 1-170 hp	4 @ 13.25/unit 32.18	4 @ 343/unit 343	29216.74
Sprayer (pre-emergence herbicide)	1- 70 hp	13.25	143	1894.75
Fertilizer Spreader	2- 70 hp 1-170 hp	2 @ 13.25/unit 32.18	2 @ 203/unit 203	11912.04
Summer Growing Season				
Sprayer (Insecticides)	1- 70 hp	13.25	143	1894.75
Sprayer (Fungicides)	1- 70 hp	13.25	143	1894.75
			TOTAL	74091.68

[1/] hp x 0.05 x 3.7853 = liters/h.

Table A-17. Equipment expected lifetime and usage per year (924 ha) for plantation establishment and maintenance operations.

Implement	Number Needed	Wear-Out Life (h)	Hours of Operation Per Year Per Implement	Expected Lifetime Per Implement (year)
170 hp tractor	1	12,000	1026	11.7
70 hp tractor (1)	1	12,000	1175	10.2
70 hp tractor (2)	1	12,000	1239	9.7
Offset Disk	1	2,500	440	5.7
Disk Harrow	3	2,500	146.67	17.1
Spreader (fertilizer)	3	800	203	3.9
Sprayer	1	1,500	572	2.6
Planter	3	1,200	342.3	3.5
Mower Conditioner	1	1,000	350	2.9

Table A-18. Cost per hour of equipment used for plantation establishment and maintenance operations.

Equipment	Assumed cost ($)	Fixed cost per Hour[1/] ($)	Variable cost per hour[2/] (hp-$)	Total cost per hour (hp-$)	Total cost per hour per operation using 70 hp tractor ($)	Total cost per hour per operation using 170 hp tractor ($)
Tractor 70 hp	17,000	2.00	2.64	4.64	--	--
Tractor 170 hp	45,000	5.60	7.02	12.62	--	--
Offset Disk	8,750	4.32	170-18.28	22.60	--	35.22
Mower-Conditioner Cutterbar	6,500	7.23	70-12.69	19.92	24.56	--
Disk Harrow	10,000	6.99	70-11.96 170-17.46	70-18.95 170-24.45	23.59	37.07
Hybrid Poplar Planter	10,000	9.58	70-35.95 170-41.45	70-45.53 170-51.03	50.17[3/]	63.65[3/]
Fertilizer	6,000	8.70	70-13.54 170-19.04	70-22.24 170-27.74	26.88	40.36[3/]
Herbicide	4,500	3.32	70-13.10	70-16.42	21.06	

1/ Includes depreciation and interest, insurance, and shelter costs.

2/ Includes cost for repairs and maintenance, labor and fuel except in the case of tractors where only repair and maintenance are included in the variable costs.

3/ Excludes costs for cuttings, fertilizer, herbicides or other materials.

Table A-19. Cost comparison between owning and renting equipment.

Operation	Field Efficiency %	Ha/h	h/Ha	Total Cost/ha[3/] 70 hp	Total Cost/ha[3] 170 hp	PA 1981 Total Cost/ha Machinery Custom Rates[2/]
Offset Disking	60	2.1	0.476	--	16.77	1. 21.00 2. 21.00 disk plowing 3. 32.00
Mower-Conditioner	56.7	2.64	0.378	9.30	--	1. 17.91 2. 16.43 mowing and 3. 17.05 conditioning
Fertilizer Spreader[1/]	50	6.07	0.164	3.39	5.62	1. 10.38 2. 10.13 dry fertilizer 3. 10.25
Sprayer Rig[1/]	53.3	6.48	0.154	3.24	--	1. 9.26 2. 9.88 spraying for 3. 9.64 weed control
Disk Harrow	60	2.1	0.476	11.23	17.65	1. 17.54 2. 19.27 disk harrowing 3. 18.41

[1/] Excluding material costs.

[2/] Costs listed are for 1) Pa. mountain section, 2) Pa. valley section, 3) State of Pennsylvania (King, 1981).

[3/] Total Cost/ha = h/ha x cost/h (from Table A-18).

APPENDIX B

TASK 2

PLANTATION BIOMASS PRODUCTION

Table B-1. Average[1] analysis of Ap and upper 15 cm of B horizon soil samples collected at various times for the 1980 planted trees at each plantation site (by treatment), Maize plots and for adjacent 25.0 m^2 permanent plots that were not fertilized and only supported native herbaceous vegetation.

Plantation Site Treatment/Sample Collection	Ap Horizon					Upper 15 cm of B Horizon				
	ph	P	K	Mg	Ca	pH	P	K	Mg	Ca
		kg/ha	(--meq/100g--)				kg/ha	(--meq/100g--)		
Basher										
Control										
Before 1st yr.	6.1	29	0.10	0.7	3.3	6.6	12	0.06	0.7	3.2
Before 2nd yr.	6.3	51	0.14	0.6	4.7	6.6	49	0.07	0.5	3.0
Before 3rd yr.	6.1	42	0.11	0.7	5.3	6.5	47	0.06	0.5	3.2
Before 4th yr.	6.0	25	0.17	1.2	6.7	6.2	28	0.12	0.9	5.5
After 4th yr.	6.1	60	0.21	0.9	6.0	6.3	48	0.14	0.8	5.8
Irrigation										
Before 1st yr.	6.1	29	0.10	0.7	3.3	6.6	12	0.06	0.7	3.2
Before 2nd yr.	6.1	62	0.22	0.7	4.4	6.4	47	0.12	0.6	3.1
Before 3rd yr.	6.1	55	0.22	0.8	5.4	6.3	61	0.12	0.7	3.8
Before 4th yr.	5.7	47	0.26	1.0	5.2	6.2	22	0.18	1.0	4.4
After 4th yr.	6.1	91	0.25	1.0	6.0	6.3	49	0.15	0.8	4.5
Fertilization										
Before 1st yr.	6.1	29	0.10	0.7	3.3	6.6	12	0.06	0.7	3.2
Before 2nd yr.	6.5	71	0.31	0.5	6.3	6.2	55	0.14	0.5	3.1
Before 3rd yr.	6.1	74	0.20	0.5	4.9	6.2	55	0.09	0.4	2.8
Before 4th yr.	6.0	99	0.52	0.9	5.8	5.9	31	0.21	0.8	5.0
After 4th yr.	6.2	158	0.36	0.6	5.1	6.3	72	0.25	0.6	4.3
Fertilization/ Irrigation										
Before 1st yr.	6.1	29	0.10	0.7	3.3	6.6	12	0.06	0.7	3.2
Before 2nd yr.	6.5	75	0.20	0.6	6.4	6.4	51	0.09	0.6	3.8
Before 3rd yr.	6.3	74	0.17	0.7	5.7	6.2	51	0.09	0.8	4.5
Before 4th yr.	6.4	64	0.32	1.1	8.3	6.2	19	0.14	1.2	5.9
After 4th yr.	6.4	123	0.41	1.1	8.4	6.3	45	0.16	1.1	5.8
Maize										
Before 1st yr.	6.1	29	0.10	0.7	3.3	6.6	12	0.06	0.7	3.2
Before 2nd yr.	6.8	59	0.16	0.8	6.0	6.9	34	0.08	0.8	4.4
Before 3rd yr.	6.4	64	0.15	0.8	6.0	6.3	76	0.09	0.9	5.1
Before 4th yr.	6.6	49	0.31	1.0	7.9	6.6	10	0.12	1.4	6.8
After 4th yr.	6.7	86	0.31	1.1	8.7	6.7	53	0.16	1.0	5.4
Native Vegetation										
Before 1st yr.	6.1	29	0.10	0.7	3.3	6.6	12	0.06	0.7	3.2
Before 2nd yr.	6.2	75	0.27	0.6	4.0	6.5	78	0.16	1.5	3.5
Before 3rd yr.	6.0	62	0.22	0.8	4.3	6.1	62	0.13	0.6	3.9
Before 4th yr.	5.8	51	0.29	1.0	5.0	6.2	7	0.10	1.0	4.5
After 4th yr.	6.0	91	0.33	0.8	5.1	6.4	77	0.25	1.1	4.9

Table B-1. (continued)

Plantation Site Treatment/Sample Collection	Ap Horizon					Upper 15 cm of B Horizon				
	ph	P	K	Mg	Ca	pH	P	K	Mg	Ca
		kg/ha	(--meq/100g---				kg/ha	(--meq/100g---		
Morrison										
Control										
Before 1st yr.	5.5	26	0.07	0.3	2.1	5.9	11	0.06	0.4	3.5
Before 2nd yr.	5.7	64	0.16	0.4	3.5	5.9	47	0.13	0.4	3.4
Before 3rd yr.	6.0	63	0.13	0.3	2.8	5.5	48	0.10	0.3	3.2
Before 4th yr.	5.4	30	0.21	0.4	2.7	5.5	17	0.16	0.5	3.5
After 4th yr.	5.7	43	0.18	0.4	3.5	5.8	72	0.16	0.5	3.5
Irrigation										
Before 1st yr.	5.5	26	0.07	0.3	2.1	5.9	11	0.06	0.4	3.5
Before 2nd yr.	5.9	45	0.13	0.4	3.5	6.2	41	0.13	0.4	4.2
Before 3rd yr.	5.6	56	0.11	0.3	3.6	5.9	31	0.10	0.4	3.5
Before 4th yr.	5.7	25	0.19	0.5	4.2	5.7	24	0.17	0.5	3.7
After 4th yr.	6.0	57	0.17	0.6	4.6	6.2	82	0.15	0.8	5.2
Fertilization										
Before 1st yr.	5.5	26	0.07	0.3	2.1	5.9	11	0.06	0.4	3.5
Before 2nd yr.	5.9	66	0.21	0.5	3.7	6.0	41	0.14	0.4	3.1
Before 3rd yr.	5.8	81	0.26	0.6	4.6	5.7	43	0.13	0.5	4.4
Before 4th yr.	6.2	65	0.43	0.8	6.7	5.2	20	0.21	0.8	4.4
After 4th yr.	6.3	110	0.36	0.8	5.7	6.2	72	0.28	0.8	6.1
Fertilization/ Irrigation										
Before 1st yr.	5.5	26	0.07	0.3	2.1	5.9	11	0.06	0.4	3.5
Before 2nd yr.	6.1	73	0.24	0.5	4.1	5.7	49	0.13	0.4	3.0
Before 3rd yr.	5.7	107	0.23	0.5	3.7	5.4	44	0.15	0.5	3.6
Before 4th yr.	6.2	72	0.44	0.7	6.5	5.3	23	0.28	0.7	3.4
After 4th yr.	6.2	132	0.30	0.8	5.1	6.0	52	0.29	0.7	4.5
Maize										
Before 1st yr.	5.5	26	0.07	0.3	2.1	5.9	11	0.06	0.4	3.5
Before 2nd yr.	6.3	81	0.21	0.5	5.6	6.0	50	0.15	0.9	5.4
Before 3rd yr.	5.9	78	0.22	0.5	4.2	5.9	74	0.16	0.6	4.6
Before 4th yr.	6.5	49	0.32	0.6	6.9	6.2	19	0.22	0.7	5.6
After 4th yr.	6.5	102	0.40	0.7	6.6	6.2	72	0.29	0.7	5.9
Native Vegetation										
Before 1st yr.	5.5	26	0.07	0.3	2.1	5.9	11	0.06	0.4	3.5
Before 2nd yr.	5.8	46	0.13	0.4	3.8	6.1	46	0.13	0.4	4.8
Before 3rd yr.	5.7	65	0.14	0.5	4.0	5.8	47	0.12	0.5	3.8
Before 4th yr.	5.6	27	0.19	0.5	4.1	5.7	30	0.15	0.5	3.6
After 4th yr.	6.0	92	0.33	0.8	5.1	6.4	77	0.25	0.9	4.6

1/ Before first year soil samples were collected March 21, 1980, and N=4. Before second year soil samples were collected November 1980 (N=3) and March 1981 (N=3) for total N=6. Before third year, before fourth year and after fourth year soil samples were collected December 1981, November 1982 and November 1983, respectively (N=3). Each soil sample was a composite of 8 plugs.

Table B-2. Average[1] analysis of Ap and upper 15 cm of B horizon soil samples collected at various times for the 1981 planted trees at each plantation site (by treatment), Maize plots and for adjacent 25.0 m^2 permanent plots that were not fertilized and only supported native herbaceous vegetation.

Plantation Site Treatment/Sample Collection	Ap Horizon					Upper 15 cm of B Horizon				
	ph	P	K	Mg	Ca	pH	P	K	Mg	Ca
		kg/ha	(--meq/100g---	)			kg/ha	(--meq/100g---	)	
Basher										
Control										
Before 1st yr.	6.0	64	0.17	0.7	3.8	6.2	45	0.12	0.6	3.2
Before 2nd yr.	5.8	74	0.91	0.9	0.8	6.1	48	0.11	0.7	2.8
Before 3rd yr.	5.7	45	0.27	1.0	4.7	5.9	17	0.17	1.3	5.3
Before 4th yr.	6.0	72	0.24	0.9	4.8	6.2	53	0.15	0.7	3.3
After 4th yr.	5.9	49	0.15	1.0	5.0	6.0	14	0.12	0.8	3.1
Irrigation										
Before 1st yr.	6.0	64	0.17	0.7	3.8	6.2	45	0.12	0.6	3.2
Before 2nd yr.	5.5	72	0.17	0.5	2.9	5.6	61	0.11	0.7	2.9
Before 3rd yr.	5.5	44	0.24	0.9	4.1	5.7	15	0.15	0.9	3.4
Before 4th yr.	5.8	90	0.20	0.7	3.7	6.0	74	0.17	0.7	3.6
After 4th yr.	5.7	13	0.16	0.8	3.6	5.9	4	0.17	1.3	4.5
Fertilization										
Before 1st yr.	6.0	64	0.17	0.7	3.8	6.2	45	0.12	0.6	3.2
Before 2nd yr.	6.3	61	0.19	0.7	6.0	5.9	46	0.07	0.7	3.1
Before 3rd yr.	6.3	64	0.35	0.9	8.1	6.0	16	0.15	1.1	4.3
Before 4th yr.	6.7	93	0.34	0.9	8.2	6.4	49	0.18	0.8	4.4
After 4th yr.	6.3	47	0.21	1.1	6.9	6.2	10	0.13	0.9	4.4
Fertilization/ Irrigation										
Before 1st yr.	6.0	64	0.17	0.7	3.8	6.2	45	0.12	0.6	3.2
Before 2nd yr.	6.4	93	0.25	0.8	6.0	6.0	88	0.11	0.7	3.3
Before 3rd yr.	6.5	94	0.42	1.1	7.1	5.7	44	0.18	0.9	4.6
Before 4th yr.	6.4	123	0.30	0.9	6.7	6.2	58	0.23	1.1	4.6
After 4th yr.	6.8	72	0.38	1.3	9.8	6.4	53	0.22	1.2	5.6
Maize										
Before 1st yr.	6.0	64	0.17	0.7	3.8	6.2	45	0.12	0.6	3.2
Before 2nd yr.	6.6	69	0.11	0.9	7.5	6.2	59	0.08	0.8	3.7
Before 3rd yr.	6.5	40	0.36	1.3	8.5	6.1	16	0.15	1.3	4.6
Before 4th yr.	6.2	81	0.31	1.2	8.1	6.4	52	0.20	1.2	6.2
After 4th yr.	6.7	42	0.22	1.1	8.1	6.4	12	0.12	1.1	4.6
Native Vegetation										
Before 1st yr.	6.0	64	0.17	0.7	3.8	6.2	45	0.12	0.6	3.2
Before 2nd yr.	6.2	46	0.11	1.1	6.1	6.2	46	0.06	0.8	3.9
Before 3rd yr.	5.9	24	0.18	1.3	7.2	6.1	9	0.14	1.5	5.2
Before 4th yr.	6.2	72	0.18	1.0	6.4	6.3	44	0.15	1.1	4.9
After 4th yr.	6.1	12	0.16	1.2	6.4	6.2	2	0.11	1.6	4.8

Table B-2. (continued)

Plantation Site Treatment/Sample Collection	Ap Horizon					Upper 15 cm of B Horizon				
	ph	P	K	Mg	Ca	pH	P	K	Mg	Ca
		kg/ha	(--meq/100g---)				kg/ha	(--meq/100g---)		
Morrison										
Control										
Before 1st yr.	6.0	44	0.14	0.4	4.0	5.7	43	0.19	0.3	3.1
Before 2nd yr.	5.5	59	0.15	0.4	3.3	5.6	49	0.14	0.5	3.8
Before 3rd yr.	5.3	29	0.24	0.5	3.4	5.3	15	0.22	0.8	3.9
Before 4th yr.	5.7	80	0.20	0.5	3.8	5.7	59	0.19	0.6	4.3
After 4th yr.	5.6	13	0.21	0.7	4.3	5.6	15	0.19	0.8	4.3
Irrigation										
Before 1st yr.	6.0	44	0.14	0.4	4.0	5.7	43	0.19	0.3	3.1
Before 2nd yr.	5.7	43	0.13	0.4	4.1	5.8	54	0.13	0.4	4.2
Before 3rd yr.	5.6	25	0.23	0.6	4.2	5.7	44	0.17	0.5	4.5
Before 4th yr.	5.8	66	0.15	0.5	4.1	6.0	44	0.18	0.5	4.4
After 4th yr.	5.6	13	0.18	0.7	3.8	5.8	3	0.13	0.6	3.9
Fertilization										
Before 1st yr.	6.0	44	0.14	0.4	4.0	5.7	43	0.19	0.3	3.1
Before 2nd yr.	5.8	115	0.31	0.5	6.0	5.6	46	0.19	0.9	5.3
Before 3rd yr.	6.1	58	0.38	0.5	6.1	5.3	31	0.26	0.9	5.4
Before 4th yr.	6.1	124	0.30	0.6	5.1	6.0	49	0.31	0.8	6.5
After 4th yr.	6.6	78	0.36	1.0	8.1	5.7	34	0.26	0.8	4.4
Fertilization/ Irrigation										
Before 1st yr.	6.0	44	0.14	0.4	4.0	5.7	43	0.19	0.3	3.1
Before 2nd yr.	5.9	78	0.26	0.5	5.0	5.7	66	0.15	0.6	4.9
Before 3rd yr.	6.5	67	0.39	0.8	9.0	5.8	31	0.23	0.7	4.7
Before 4th yr.	6.2	105	0.32	0.8	5.6	5.8	72	0.26	0.7	4.9
After 4th yr.	6.3	50	0.26	0.9	7.9	6.1	38	0.22	0.9	6.6
Maize										
Before 1st yr.	6.0	44	0.14	0.4	4.0	5.7	43	0.19	0.3	3.1
Before 2nd yr.	6.5	108	0.15	0.5	6.6	6.0	70	0.11	0.5	3.8
Before 3rd yr.	6.2	36	0.27	0.6	5.2	5.9	39	0.19	0.6	4.0
Before 4th yr.	6.2	81	0.31	1.2	8.1	6.4	52	0.20	1.2	6.2
After 4th yr.	6.6	27	0.25	1.0	6.8	6.3	34	0.18	0.8	5.0
Native Vegetation										
Before 1st yr.	6.0	44	0.14	0.4	4.0	5.7	43	0.19	0.3	3.1
Before 2nd yr.	5.8	59	0.18	2.0	3.6	5.8	34	0.22	2.5	5.2
Before 3rd yr.	5.5	27	0.22	1.8	4.0	5.7	30	0.24	2.1	4.2
Before 4th yr.	6.2	72	0.18	1.0	6.4	6.4	44	0.15	1.1	4.9
After 4th yr.	6.0	11	0.21	2.3	4.9	6.1	9	0.22	2.6	4.9

1/ Before first year soil samples were collected March 21, 1980, and N=4. Before second, third and fourth year soil samples were collected December 1981, November 1982 and November 1983, respectively (N=3). Each soil sample was a composite of 8 plugs.

Table B-3. Amount of fertilizer and lime applied at the start of the second growing season and accumulated total fertilizer and lime for the 1980 planted replications (1, 2 and 3) and 1981 planted replications (4, 5 and 6), by site, treatment and replication.

1980 Plantation Site Treatment-Replication		Beginning of 2nd Growing Season					Accumulative for 1 and 2 Growing Seasons[6/]				
		N[1/]	P_2O_5[2/]	K_2O[4/]	Lime[4/]	Mg[5/]	N	P_2O_5	K_2O	Lime	Mg
		kg/ha									
Basher											
Fertilization	1	168	76	188	0	157	347	255	367	3093	157
	2	168	43	17	3362	118	347	222	196	6455	118
	3	168	73	11	2242	101	347	252	190	5335	101
	Average	168	64	72	1868	125	347	243	251	4961	125
Fertilization/ Irrigation	1	168	71	123	2802	106	347	250	302	5895	106
	2	168	93	202	0	84	347	272	381	3093	84
	3	168	54	145	0	56	347	233	324	3093	56
	Average	168	73	157	934	82	347	252	336	4027	82
Morrison											
Fertilization	1	168	112	194	4483	134	347	291	396	10603	280
	2	168	104	138	5604	146	347	283	340	11724	292
	3	168	67	104	2802	95	347	246	360	8922	241
	Average	168	94	145	4296	125	347	273	365	10416	271
Fertilization/ Irrigation	1	168	112	93	2242	101	347	291	396	8362	247
	2	168	56	87	3923	106	347	235	289	10043	252
	3	168	82	151	3923	123	347	261	353	10043	263
	Average	168	83	110	3363	110	347	262	312	9483	254

Table B-3. (continued)

1981 Plantation Site Treatment-Replication		Beginning of 2nd Growing Season					Accumulative for 1 and 2 Growing Seasons[6/]				
		N[1/]	P_2O_5[2/]	K_2O[4/]	Lime[4/]	Mg[5/]	N	P_2O_5	K_2O	Lime	Mg
		kg/ha									
Basher											
Fertilization	4	168	61	224	0	0	336	176	413	4343	86
	5	168	118	168	0	67	336	232	357	4343	153
	6	168	140	118	3362	101	336	254	307	7705	187
	Average	168	106	170	1121	56	336	220	359	5464	142
Fertilization/ Irrigation	4	168	61	196	0	56	336	176	385	4343	142
	5	168	34	11	1121	78	336	148	200	5464	164
	6	168	118	207	2242	0	336	232	396	6585	86
	Average	168	71	138	1121	45	336	185	327	5464	131
Morrison											
Fertilization	4	168	34	34	2242	168	336	168	202	7004	319
	5	168	84	101	5604	179	336	218	269	10366	330
	6	168	34	157	4483	134	336	168	325	9245	285
	Average	168	51	97	4110	160	336	185	265	8872	311
Fertilization/ Irrigation	4	168	118	219	4483	112	336	252	387	9245	263
	5	168	95	95	4483	168	336	229	263	9245	319
	3	168	34	11	1121	123	336	168	179	5883	274
	Average	168	82	108	3362	134	336	216	276	8124	285

1/ Broadcast application of ammonium nitrate at 33% N in May, after bud break.

2/ Broadcast application in March of triple superphosphate at 46% P_2O_5.

3/ Broadcast application in March of potassium chloride at 60% K_2.

4/ Broadcast application in March of ground limestone with a minimum CaO for 51% and $CaCO_3$ equivalent of 92.28%.

5/ Broadcast application in March of ground dolomitic limestone with a minimum MgO of 11%, minimum CaO of 35%, and a $CaCO_3$ equivalent of 89% for all treatments requiring lime. For treatments not requiring lime, MgO at 58% Mg was used.

6/ See Table 1-1 for before 1st growing season fertilizer and lime specifications.

Table B-4. Amount of fertilizer and lime applied at the start of the third growing season and accumulated total fertilizer and lime for the 1980 planted replications (1, 2 and 3) and 1981 planted replications (4, 5 and 6), by site, treatment and replication.

1980 Plantation Site Treatment-Replication		Beginning of 3rd Growing Season					Accumulative for 1, 2 and 3 Growing Seasons[6/]				
		N[1/]	P_2O_5[2/]	K_2O[4/]	Lime[4/]	Mg[5/]	N	P_2O_5	K_2O	Lime	Mg
		kg/ha									
Basher											
Fertilization	1	168	84	224	1121	101	515	339	591	4214	258
	2	168	84	123	3362	123	515	306	319	9817	241
	3	168	62	151	5604	134	515	314	341	10939	235
	Average	168	77	166	3362	119	515	320	417	8323	235
Fertilization/ Irrigation	1	168	101	174	1121	56	515	351	476	7016	162
	2	168	62	219	0	0	515	334	600	3093	84
	3	168	67	146	1121	56	515	300	470	4214	112
	Average	168	77	180	747	37	515	328	515	4774	119
Morrison											
Fertilization	1	168	62	62	2242	90	515	353	458	12845	370
	2	168	62	78	4483	134	515	345	418	16207	426
	3	168	106	191	4483	112	515	352	551	13405	353
	Average	168	77	110	3736	112	515	350	476	14152	383
Fertilization/ Irrigation	1	168	34	112	4483	123	515	325	508	12845	370
	2	168	34	123	4483	101	515	269	412	14526	353
	3	168	112	151	4483	101	515	373	505	14526	364
	Average	168	60	129	4483	108	515	322	475	13966	362

Table B-4. (continued)

1981 Plantation Site Treatment-Replication		Beginning of 3rd Growing Season					Accumulative for 1, 2 and 3 Growing Seasons[6/]				
		N[1/]	P_2O_5[2/]	K_2O[4/]	Lime[4/]	Mg[5/]	N	P_2O_5	K_2O	Lime	Mg
		kg/ha									
Basher											
Fertilization	4	168	134	11	0	0	504	310	424	4343	86
	5	168	67	101	2242	67	504	299	458	6585	220
	6	168	101	118	4483	101	504	355	425	12188	288
	Average	168	101	77	2242	56	504	321	436	7706	198
Fertilization/ Irrigation	4	168	45	11	0	0	504	221	396	4343	142
	5	168	34	11	2242	56	504	182	211	7706	220
	6	168	118	129	0	0	504	350	525	6585	86
	Average	168	66	50	747	19	504	251	377	6211	150
Morrison											
Fertilization	4	168	151	78	3364	90	504	319	280	10368	409
	5	168	118	11	4483	168	504	336	280	14849	468
	6	168	118	11	0	134	504	286	336	9245	419
	Average	168	129	33	2616	131	504	314	298	20733	442
Fertilization/ Irrigation	4	168	151	11	3364	112	504	403	398	12609	375
	5	168	62	84	0	123	504	291	347	9245	442
	3	168	62	11	0	90	504	230	190	5883	364
	Average	168	92	35	1121	108	504	308	311	9245	393

1/ Broadcast application of ammonium nitrate at 33% N in May, after bud break.

2/ Broadcast application in March of triple superphosphate at 46% P_2O_5.

3/ Broadcast application in March of potassium chloride at 60% K_2.

4/ Broadcast application in March of ground limestone with a minimum CaO for 51% and $CaCO_3$ equivalent of 92.28%.

5/ Broadcast application in March of ground dolomitic limestone with a minimum MgO of 11%, minimum CaO of 35%, and a $CaCO_3$ equivalent of 89% for all treatments requiring lime. For treatments not requiring lime, MgO at 58% Mg was used.

6/ See Table 1-1 for before 1st growing season and Table B-3 for before 2nd growing season fertilizer and lime specifications.

Table B-5. Amount of fertilizer and lime applied at the start of the fourth growing season and accumulated total fertilizer and lime for the 1980 planted replications (1, 2 and 3) and 1981 planted replications (4, 5 and 6), by site, treatment and replication.

1980 Plantation Site Treatment-Replication		Beginning of 4th Growing Season					Accumulative for 1, 2, 3 and 4 Growing Seasons[6/]				
		N[1/]	P_2O_5[2/]	K_2O[4/]	Lime[4/]	Mg[5/]	N	P_2O_5	K_2O	Lime	Mg
		kg/ha									
Basher											
Fertilization	1	168	34	11	0	0	683	373	602	4214	258
	2	168	34	11	4483	112	683	340	330	14300	353
	3	168	34	11	3362	134	683	348	352	14301	369
	Average	168	34	11	2615	82	683	354	428	10938	327
Fertilization/ Irrigation	1	168	34	11	0	78	683	385	487	7016	240
	2	168	151	224	2242	0	683	485	824	5335	84
	3	168	118	78	3362	45	683	418	548	7576	157
	Average	168	101	104	1868	41	683	429	619	6642	160
Morrison											
Fertilization	1	168	62	11	0	90	683	415	469	12874	460
	2	168	45	11	0	78	683	390	429	16207	504
	3	168	62	11	2242	146	683	414	562	15647	499
	Average	168	56	11	747	105	683	406	487	14909	488
Fertilization/ Irrigation	1	168	62	11	0	90	683	387	519	12845	460
	2	168	118	11	2242	101	683	387	423	16768	454
	3	168	62	11	3362	90	683	435	515	17888	454
	Average	168	81	11	1868	94	683	403	486	15834	456

Table B-5. (continued)

1981 Plantation Site Treatment-Replication		Beginning of 4th Growing Season					Accumulative for 1, 2, 3, and 4 Growing Seasons[6/]				
		N[1/]	P_2O_5[2/]	K_2O[4/]	Lime[4/]	Mg[5/]	N	P_2O_5	K_2O	Lime	Mg
		kg/ha									
Basher											
Fertilization	4	168	123	22	0	0	672	433	446	4343	86
	5	168	34	50	0	0	672	333	508	6585	220
	6	168	62	11	0	0	672	417	436	12188	288
	Average	168	73	28	0	0	672	394	463	7706	198
Fertilization/ Irrigation	4	168	34	95	0	0	672	255	491	4343	142
	5	168	34	62	3362	67	672	216	273	11068	287
	6	168	62	39	0	0	672	412	564	6585	86
	Average	168	43	65	1121	22	672	294	443	7332	172
Morrison											
Fertilization	4	168	34	50	0	67	672	353	330	10368	476
	5	168	34	134	4483	123	672	370	414	19332	591
	6	168	34	11	3362	123	672	320	347	12607	542
	Average	168	34	65	2615	104	672	348	364	14102	536
Fertilization/ Irrigation	4	168	62	11	0	0	672	465	409	12609	375
	5	168	34	73	4483	123	672	325	420	13728	565
	3	168	34	67	2242	45	672	264	257	8125	409
	Average	168	43	50	2242	56	672	351	362	11487	450

1/ Broadcast application of ammonium nitrate at 33% N in May, after bud break.

2/ Broadcast application in March of triple superphosphate at 46% P_2O_5.

3/ Broadcast application in March of potassium chloride at 60% K_2.

4/ Broadcast application in March of ground limestone with a minimum CaO for 51% and $CaCO_3$ equivalent of 92.28%.

5/ Broadcast application in March of ground dolomitic limestone with a minimum MgO of 11%, minimum CaO of 35%, and a $CaCO_3$ equivalent of 89% for all treatments requiring lime. For treatments not requiring lime, MgO at 58% Mg was used.

6/ See Table 1-1 for before 1st growing season and Table B-3 for before 2nd growing season and Table B-4 for before 3rd growing season fertilizer and lime specifications.

Table B-6. Average[1/] weekly maximum and minimum temperatures, and rainfall for the Basher and Morrison plantation sites in 1982.

Week Starting	Weekly Maximum Temperature		Weekly Minimum Temperature		Weekly Rainfall	
	Basher	Morrison	Basher	Morrison	Basher	Morrison
	(- - - - - - - - - - C°- - - - - - - - - -)				(- - - cm - - -)	
May 16	23.3	23.8	13.3	13.3	2.03	2.54
May 23	21.1	20.4	14.4	14.4	1.40	1.27
May 30	21.7	19.9	12.7	11.8	5.21	7.62
June 6	22.9	20.2	13.6	12.8	3.43	3.43
June 13	26.0	23.7	12.4	12.9	2.54	2.79
June 20	25.0	24.2	8.7	9.2	2.03	3.56
June 27	25.6	24.6	10.9	12.5	2.00	2.03
July 4	28.6	27.4	15.7	15.6	2.29	2.29
July 11	28.4	29.1	16.2	16.5	0.71	0.38
July 18	30.6	29.6	14.5	14.5	2.54	1.91
July 25	27.8	26.8	14.9	11.2	5.08	5.71
August 1	28.7	28.2	16.0	16.7	0.00	0.13
August 8	24.6	25.1	12.2	12.0	1.78	0.64
August 15	26.8	24.6	10.1	9.0	0.00	1.12
August 22	24.2	23.4	8.9	10.3	2.03	2.03
August 29	24.7	24.3	13.0	12.6	1.14	1.65
Sept. 5	26.1	25.2	13.3	12.5	0.00	0.00
Sept. 12	26.3	25.2	10.2	8.1	0.38	0.00

[1/] From daily maximum and minimum values as measured by a hydrothermograph at each site.

Table B-7. Amount of water applied[1/] at the Basher site in 1982 to two and three year old trees by treatment and replication.

Tree Age	Treatment	Replication	Amount of Water by Irrigation in 1982						
			Aug 16-18	Aug 19-23	Aug 23-25	Aug 26-27	Aug 30-31	Sept 3	Total[2/]
			liters/meter^2						
Two year old									
	Irrigation	4	12.73	12.73	12.73	0.00	12.73	3.66	54.58
		5	12.73	12.73	12.73	0.00	0.00	3.66	41.85
		6	12.73	12.73	12.73	12.73	12.73	3.66	67.31
		Average[3/]	12.73	12.73	12.73	4.24	8.49	3.66	54.58
	Fertilization/ Irrigation	4	12.73	12.73	12.73	12.73	12.73	3.66	67.31
		5	25.46	12.73	12.73	0.00	0.00	3.66	54.58
		6	0.00	0.00	25.46	12.73	12.73	3.66	54.58
		Average[3/]	12.73	8.49	16.97	8.49	8.49	3.66	58.82
Three year old									
	Irrigation	1	25.46	12.73	12.73	12.73	12.73	3.66	80.04
		2	12.73	12.73	12.73	12.73	16.39	3.66	70.97
		3	12.73	12.73	12.73	12.73	12.73	3.66	67.31
		Average[3/]	16.97	12.73	12.73	12.73	13.95	3.66	72.77
	Fertilization/ Irrigation	1	25.46	12.73	12.73	12.73	12.73	3.66	80.04
		2	12.73	12.73	12.73	12.73	12.73	3.66	67.31
		3	12.73	12.73	12.73	12.73	12.73	3.66	67.31
		Average[3/]	16.97	12.73	12.73	12.73	12.73	3.66	71.55

[1/] Amount of water added to each replication-treatment unit was determined from baseline upper 20 cm soil water characteristics (see Table A-9). Amount of water in the soil was checked 24 hours after irrigation to verify the upper 20 cm of soil had sufficient water. If not, irrigation was repeated.

[2/] Determined from actual amounts added in gallons/517.44 m^2. Individual irrigations may not add to total due to rounding.

[3/] Average is only a summary value.

Table B-8. Amount of water applied[1/] at the Morrison site in 1982 to two and three year old trees by treatment and replication.

Tree Age	Treatment	Replication	Amount of Water by Irrigation in 1982							
			May 7-10	May 11-12	May 13-14	May 17-19	May 20-21	June 13-14	June 15-16	Sub Total 1[2/]
			liters/meter^2							
Two year old										
	Irrigation	4	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		5	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		6	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		Average[3/]	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
	Fertilization/ Irrigation	4	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		5	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		6	12.97	12.73	12.73	12.73	12.73	12.73	12.73	90.35
		Average[3/]	13.14	12.73	12.73	12.73	12.73	12.73	12.73	89.52
Three year old										
	Irrigation	1	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		2	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		3	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		Average[3/]	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
	Fertilization/ Irrigation	1	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		2	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		3	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		Average[3/]	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11

Table B-8. (continued)

Tree Age	Treatment	Replication	Amount of Water by Irrigation in 1982							
			June 19-21	June 26-27	Aug 4-6	Aug 6-11	Aug 11-13	Aug 16-18	Aug 20-23	Sub Total 2[2/]
			liters/meter^2							
Two year old										
	Irrigation	4	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		5	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		6	12.73	0.00	12.73	12.73	12.73	12.73	12.73	76.38
		Average[3/]	12.73	8.49	12.73	12.73	12.73	12.73	12.73	84.87
	Fertilization/ Irrigation	4	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		5	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		6	12.73	0.00	12.73	12.73	12.73	12.73	12.73	76.38
		Average[3/]	12.73	8.49	12.73	12.73	12.73	12.73	12.73	84.87
Three year old										
	Irrigation	1	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		2	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		3	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		Average[3/]	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
	Fertilization/ Irrigation	1	12.73	0.00	12.73	12.73	12.73	12.73	12.73	76.38
		2	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		3	12.73	12.73	12.73	12.73	12.73	12.73	12.73	89.11
		Average[3/]	12.73	8.49	12.73	12.73	12.73	12.73	12.73	84.87

Table B-8. (continued)

Tree Age	Treatment	Replication	Amount of Water by Irrigation in 1982						
			Aug 26	Aug-Sept 30-2	Sept 3	Sub[2/] Total 3	Sub[2/] Total 2	Sub[2/] Total 1	Total
			- - - - - - - - - - - - - - liters/meter^2 - - - - - - - - - - - - - -						
Two year old									
	Irrigation	4	12.73	12.73	3.66	29.12	89.11	89.11	207.34
		5	12.73	12.73	3.66	29.12	89.11	89.11	207.34
		6	12.73	12.73	3.66	29.12	76.38	89.11	194.61
		Average[3/]	12.73	12.73	3.66	29.12	84.87	89.11	203.10
	Fertilization/ Irrigation	4	12.73	12.73	3.66	29.12	89.11	89.11	207.34
		5	12.73	12.73	3.66	29.12	89.11	89.11	207.34
		6	12.73	12.73	3.66	29.12	76.38	90.35	195.85
		Average[3/]	12.73	12.73	3.66	29.12	84.87	89.52	203.51
Three year old									
	Irrigation	1	12.73	12.73	3.66	29.12	89.11	89.11	207.34
		2	12.73	12.73	3.66	29.12	89.11	89.11	207.34
		3	12.73	12.73	3.66	29.12	89.11	89.11	207.34
		Average[3/]	12.73	12.73	3.66	29.12	89.11	89.11	207.34
	Fertilization/ Irrigation	1	12.73	12.73	3.66	29.12	76.38	89.11	194.61
		2	12.73	12.73	3.66	29.12	89.11	89.11	207.34
		3	12.73	12.73	3.66	29.12	89.11	89.11	207.34
		Average[3/]	12.73	12.73	3.66	29.12	84.87	89.11	203.10

[1/] Amount of water added to each replication-treatment unit was determined from baseline upper 20 cm soil water characteristics (see Table A-10). Amount of water in the soil was checked 24 hours after irrigation to verify the upper 20 cm of soil had sufficient water. If not, irrigation was repeated.

[2/] Determined from actual amounts added in gallons/517.44 m^2. Individual irrigtions may not add to total due to rounding.

[3/] Average is only a summary value.

Table B-9. Average[1/] weekly maximum and minimum temperatures, and rainfall for the Basher and Morrison plantations in 1983.

Week Starting	Weekly Maximum Temperature		Weekly Maximum Temperature		Weekly Rainfall	
	Basher	Morrison	Basher	Morrison	Basher	Morrison
	(- - - - - - - - - - - - - - - C°- - - - - - - - - - - - - - -)				(- - - - cm - - - -)	
May 30	23.8	24.0	9.1	9.1	0.05	0.05
June 6	26.9	27.1	9.0	9.1	0.00	0.00
June 13	29.7	27.9	14.5	15.0	1.27	1.27
June 20	28.7	27.3	10.8	10.8	3.81	4.06
June 27	28.6	27.5	16.5	16.7	1.80	1.80
July 4	26.9	24.9	10.0	9.4	0.00	0.00
July 11	31.9	31.2	15.6	16.3	0.00	0.00
July 18	29.3	28.5	15.2	15.0	3.04	3.30
July 25	30.2	30.0	13.0	14.9	0.00	0.00
Aug 1	28.0	28.8	11.4	15.0	0.00	0.00
Aug 8	-	26.2	-	13.9	0.76	0.86
Aug 15	30.7	30.6	13.3	14.2	1.02	1.02
Aug 22	29.0	28.7	14.5	15.2	0.00	0.00
Total	-	-	-	-	11.75	12.36

[1/] From daily maximum and minimum values as measured by hydrothermograph at each site.

Table B-10. Amount of water applied[1/] at the Basher site in 1983 to three and four year old trees by treatment and replication.

Tree Age	Treatment	Replication	Amount of Water by Irrigation in 1983					
			July 25-29	Aug 1-8	Aug 8-11	Aug 11-16	Aug 16-19	Sub Total 1[2/]
			liters/meter^2					
Three year old								
	Irrigation	4	6.95	12.73	12.73	12.73	12.73	57.87
		5	9.51	12.73	12.73	15.29	12.73	62.99
		6	6.95	12.73	14.78	12.73	12.73	59.92
		Average[3/]	7.80	12.73	13.41	13.58	12.73	60.25
	Fertilization/ Irrigation	4	13.53	12.73	12.73	12.73	12.73	64.45
		5	7.68	12.73	12.73	12.73	12.73	58.60
		6	6.95	12.73	12.73	12.73	12.73	57.87
		Average[3/]	9.39	12.73	12.73	12.73	12.73	60.31
Four year old								
	Irrigation	1	17.41	13.46	12.73	12.73	12.73	69.06
		2	4.61	12.73	12.73	12.73	12.73	55.53
		3	7.10	12.73	12.73	12.73	12.73	58.02
		Average[3/]	9.71	12.97	12.73	12.73	12.73	60.87
	Fertilization/ Irrigation	1	4.83	12.36	12.73	12.73	12.73	55.38
		2	3.66	13.86	12.73	12.73	12.73	55.71
		3	12.88	12.73	12.73	12.73	12.73	63.80
		Average[3/]	7.12	12.98	12.73	12.73	12.73	58.29

Table B-10. (continued)

Tree Age	Treatment	Replication	Amount of Water by Irrigation in 1983				
			Aug 19-25	Aug 25-30	Sub Total 2 [2/]	Sub Total 1 [2/]	Total
			liters/meter^2				
Two year old							
	Irrigation	4	12.73	12.73	25.46	57.87	83.33
		5	12.73	12.73	25.46	62.99	88.45
		6	12.73	12.73	25.46	59.92	85.38
		Average [3/]	12.73	12.73	25.46	60.25	85.71
	Fertilization/ Irrigation	4	12.73	12.73	25.46	64.45	89.91
		5	12.73	12.73	25.46	58.60	84.06
		6	12.73	12.73	25.46	57.87	83.33
		Average [3/]	12.73	12.73	25.46	60.31	85.77
Three year old							
	Irrigation	1	12.73	12.73	25.46	69.06	94.52
		2	12.73	12.73	25.46	55.53	80.99
		3	12.73	9.80	22.53	58.02	80.55
		Average [3/]	12.73	11.75	24.48	60.87	85.35
	Fertilization/ Irrigation	1	12.73	12.73	25.46	55.38	80.84
		2	12.73	12.73	25.46	55.71	81.17
		3	12.73	12.73	25.46	63.80	89.26
		Average [3/]	12.73	12.73	25.46	58.29	83.75

[1/] Amount of water added to each replication-treatment unit was determined from baseline upper 20 cm soil water characteristics (see Table A-9). Amount of water in the soil was checked 24 hours after irrigation to verify the upper 20 cm of soil had sufficient water. If not, irrigation was repeated.

[2/] Determined from actual amounts added in gallons/517.44 m^2. Individual irrigations may not add to total due to rounding.

[3/] Average is only a summary value.

Table B-11. Amount of water applied[1/] at the Morrison site in 1983 to three and and four year old trees, by treatment and replication.

Tree Age	Treatment	Replication	Amount of Water by Irrigation in 1983					
			July 11-15	July 18-19	July 20-22	July 22-26	July-Aug 28-2	Sub[2/] Total 1
			- - - - - - - - - - - - - - liters/meter^2 - - - - - - - - - - - - - -					
Three year old								
	Irrigation	4	22.31	12.73	12.73	15.66	12.73	76.16
		5	12.73	12.73	12.73	12.73	12.73	63.65
		6	16.10	12.73	12.73	12.73	12.73	67.02
		Average[3/]	17.05	12.73	12.73	13.71	12.73	68.95
	Fertilization/ Irrigation	4	15.22	12.73	12.73	12.73	12.73	66.14
		5	18.14	12.73	12.73	12.73	12.73	69.06
		6	28.53	12.73	13.46	12.73	12.73	80.18
		Average[3/]	20.63	12.73	12.97	12.73	12.73	71.79
Three year old								
	Irrigation	1	14.08	12.73	12.73	12.73	12.73	65.00
		2	0.00	12.73	12.73	12.73	12.73	50.92
		3	13.46	12.73	12.73	12.73	12.73	64.38
		Average[3/]	9.18	12.73	12.73	12.73	12.73	60.10
	Fertilization/ Irrigation	1	34.71	12.73	12.73	12.73	12.73	85.63
		2	12.73	14.05	13.46	12.73	12.73	65.70
		3	12.73	12.73	12.73	12.73	12.73	63.65
		Average[3/]	20.06	13.17	12.97	12.73	12.73	71.66

Table B-11. (continued)

Tree Age	Treatment	Replication	Amount of Water by Irrigation in 1983					
			Aug 2-8	Aug 9-11	Aug 12-16	Aug 17-19	Aug 19-25	Sub Total 2/ 2
			liters/meter^2					
Three year old								
	Irrigation	4	15.88	12.73	12.73	12.73	12.73	66.80
		5	12.73	12.73	12.73	12.73	12.73	63.65
		6	12.73	12.73	12.73	12.73	12.73	63.65
		Average 3/	13.78	12.73	12.73	12.73	12.73	64.70
	Fertilization/ Irrigation	4	12.73	12.73	12.73	12.73	12.73	63.65
		5	12.73	19.02	21.95	12.73	12.73	79.16
		6	12.73	12.73	12.73	12.73	12.73	63.65
		Average 3/	12.73	14.83	15.80	12.73	12.73	68.82
Four year old								
	Irrigation	1	12.73	12.73	12.73	12.73	12.73	63.65
		2	12.73	12.73	12.73	12.73	12.73	63.65
		3	12.73	12.73	12.73	12.73	12.73	63.65
		Average 3/	12.73	12.73	12.73	12.73	12.73	63.65
	Fertilization/ Irrigation	1	12.73	12.73	12.73	12.73	12.73	63.65
		2	12.73	12.73	12.73	12.73	12.73	63.65
		3	12.73	12.73	12.73	12.73	12.73	63.65
		Average 3/	12.73	12.73	12.73	12.73	12.73	63.65

Table B-11. (continued)

Tree Age	Treatment	Replication	Amount of Water by Irrigation in 1983					
			Aug 26-30	Aug-Sept 30-9	Sub Total 3	Sub Total 2	Sub Total 1	Total
			- - - - - - - - - - - - - - liters/meter^2 - - - - - - - - - - - - - -					
Three year old								
	Irrigation	4	12.73	12.73	25.46	66.80	76.16	168.42
		5	12.73	12.73	25.46	63.65	63.65	152.76
		6	12.73	0.00	12.73	63.65	67.02	143.40
		Average 3/	12.73	8.49	21.22	64.70	68.95	154.87
	Fertilization/ Irrigation	4	12.73	12.73	25.46	63.65	66.14	155.25
		5	12.73	12.73	25.46	79.16	69.06	173.68
		6	12.73	0.00	12.73	63.65	80.18	156.56
		Average 3/	12.73	8.49	21.22	68.82	71.79	161.83
Four year old								
	Irrigation	1	12.73	0.00	12.73	63.65	65.00	141.38
		2	12.73	12.73	25.46	63.65	50.92	140.03
		3	12.73	12.73	25.46	63.65	64.38	153.49
		Average 3/	12.73	8.49	21.22	63.65	60.10	144.97
	Fertilization/ Irrigation	1	12.73	0.00	12.73	63.65	85.63	162.01
		2	12.73	12.73	25.46	63.65	65.70	154.81
		3	12.73	12.73	25.46	63.65	63.65	152.76
		Average 3/	12.73	8.49	21.22	63.65	71.66	156.53

1/ Amount of water added to each replication-treatment unit was determined from baseline upper 20 cm soil water characteristics (see Table A-10). Amount of water in the soil was checked 24 hours after irrigation to verify the upper 20 cm of soil had sufficient water. If not, irrigation was repeated.

2/ Determined from actual amounts added in gallons/517.44 m^2. Individual irrigations may not add to total due to rounding.

3/ Average is only of summary value.

Table B-12. Average[1/] weekly maximum and minimum temperatures, and rainfall for the Basher and Morrison plantation sites in 1984.

Week Starting	Weekly Maximum Temperature		Weekly Minimum Temperature		Weekly Rainfall Temperature	
	Basher	Morrison	Basher	Morrison	Basher	Morrison
	(- - - - - - - - - - C°- - - - - - - - - -)				(- - - -cm- - - -)	
June 4	32.4	32.6	19.7	17.2	0.00	0.00
June 11	24.4	24.5	12.9	13.2	6.43	4.57
June 18	27.0	25.2	17.9	12.9	2.67	2.72
June 25	24.0	23.6	11.2	10.9	4.17	4.78
July 2	24.5	26.7	13.0	14.1	2.29	1.91
July 9	28.5	24.5	13.3	13.5	0.33	0.46
July 16	26.3	25.2	15.2	13.3	1.14	0.99
July 23	27.3	25.2	13.4	12.1	0.00	0.79
July 30	21.4	26.4	16.9	15.9	4.06	3.56
Aug 6	28.9	27.2	18.7	18.8	9.40	7.75
Aug 13	28.3	26.7	16.7	15.9	5.72	2.92
Aug 20	26.7	24.6	9.7	9.5	1.70	1.83
Aug 27	25.6	26.4	16.4	14.9	0.00	1.02

[1/] From daily maximum and minimum values as measured by a hydrothermograph at each site.

Table B-13. Amount of water applied[1/] in 1984 at the Basher site to first rotation four year old trees and second rotation one year old trees by treatment and replication.

Tree age	Treatment	Replication	Amount of Water by Irrigation Dates: June 26-28	June 29	July 23-25	July 25-30	July-Aug 31-6	Total[2/]
			liters/meters^2					
Four year old -	First rotation Irrigation	4	12.73	0.00	12.73	12.73	0.00	38.19
		5	12.73	0.00	12.73	12.73	12.73	50.92
		6	12.73	0.00	12.73	12.73	0.00	38.19
		Average[3/]	12.73	0.00	12.73	12.73	4.23	42.43
	Fertilization/ Irrigation	4	12.73	0.00	12.73	12.73	0.00	38.19
		5	12.73	0.00	12.73	17.74	12.73	55.93
		6	12.73	0.00	12.73	12.73	0.00	38.19
		Average[3/]	12.73	0.00	12.73	14.40	4.23	44.10
One year old -	Second Rotation Irrigation	1	4.68	20.78	16.09	12.73	12.73	67.01
		2	12.73	0.00	12.73	12.73	12.73	50.92
		3	12.73	0.00	12.73	12.73	12.73	50.92
		Average[3/]	10.05	6.93	13.85	12.73	12.73	56.28
	Fertilization/	1	12.73	12.73	12.73	12.73	12.73	63.65
		2	12.73	12.73	12.73	12.73	12.73	63.65
		3	12.73	0.00	12.73	12.73	12.73	50.92
		Average[3/]	12.73	8.49	12.73	12.73	12.73	59.41

[1/] Amount of water added to each replication-treatment unit was determined from baseline upper 20 cm soil water characteristics (see Table A-9). Amount of water in the soil was checked 24 hours after irrigation to verify the upper 20 cm of soil had sufficient water. If not, irrigation was repeated.

[2/] Determined from actual amounts added in gallons/517.44 m^2. Individual irrigation may not add to total due to rounding.

[3/] Average is only of summary value.

Table B-14. Amount of water applied[1/] in 1984 at the Morrison site to first rotation four year old trees and second rotation one year old trees by treatment and replication.

Tree age	Treatment	Replication	June 13-15	June 20-22	June-July 24-4	July 17-20	July 23-25	July 26-1	Aug 1-6	Total[2/]
			Amount of Water by Irrigation Dates (liters/meters^2)							
Four year old	- First rotation Irrigation	4	12.73	12.88	16.39	13.46	12.73	12.73	12.73	93.65
		5	12.73	12.73	12.73	13.85	14.99	12.73	12.73	92.49
		6	16.53	12.73	0.00	12.73	12.73	12.73	0.00	67.45
		Average	13.99	12.88	9.71	13.35	13.48	12.73	8.49	84.53
	Fertilization/ Irrigation	4	8.85	12.73	12.73	12.73	12.73	12.73	12.73	85.23
		5	12.73	12.73	12.73	14.38	12.73	12.73	12.73	90.76
		6	17.56	19.31	0.00	12.73	13.53	12.73	0.00	75.86
		Average	13.05	14.92	8.49	13.28	13.00	12.73	8.49	83.95
One year old	- Second Rotation Irrigation	1	12.73	13.46	12.73	12.73	13.75	12.73	12.73	90.86
		2	12.73	12.73	12.73	25.97	12.73	12.73	12.73	102.35
		3	12.73	13.46	12.73	12.97	16.09	12.73	12.73	93.44
		Average	12.73	13.22	12.73	17.14	13.86	12.73	12.73	95.55
	Fertilization/ Irrigation	1	12.73	12.73	0.00	13.24	12.73	12.73	12.73	76.89
		2	13.31	12.73	12.73	12.73	12.73	12.73	12.73	89.69
		3	12.73	12.73	12.73	14.56	12.73	12.73	14.48	92.69
		Average	12.92	12.73	8.49	13.51	12.73	12.73	13.31	86.42

1/ Amount of water added to each replication-treatment unit was determined from baseline upper 20 cm soil water characteristics (see Table A-10). Amount of water in the soil was checked 24 hours after irrigation to verify the upper 20 cm of soil had sufficient water. If not, irrigation was repeated.

2/ Determined from actual amounts added in gallons/517.44 m^2. Individual irrigation may not add to total due to rounding.

3/ Average is only of summary value.

Table B-15. Second growing season average[1/] elongation by plantation site treatment and measurement date for the 1980 planted trees. Each value is from 30 completely independent observations per site per treatment.

Plantation Site Treatment	Second Growing Season Elongation by Measurement Date							
	June 19	July 2	July 17	July 31	Aug 14	Aug 28	Sept 10	Sept 29
	meters							
Basher								
Control	0.31 e	0.45 c	0.88 c	0.94 d	1.19 c	0.88 d	1.18 e	1.45 d
Irrigation	0.37 d	0.69 b	0.91 c	1.21 c	1.66 b	1.75 c	1.99 d	1.91 c
Fertilization	0.50 ab	0.75 ab	1.31 a	1.66 a	2.19 a	2.32 a	2.39 bc	2.45 b
Fertilization/ Irrigation	0.45 ac	0.81 a	1.18 b	1.43 b	2.04 a	2.20 ab	2.58 b	2.54 b
Average	0.41	0.67	1.07	1.31	1.77	1.79	2.03	2.09
Morrison								
Control	0.26 e	0.38 c	0.55 d	0.62 f	0.72 d	0.58 e	0.66 f	0.71 f
Irrigation	0.26 e	0.43 c	0.62 d	0.78 e	0.80 d	0.97 d	1.01 e	1.14 e
Fertilization	0.40 cd	0.68 b	0.96 c	1.38 b	1.72 b	2.04 b	2.27 c	2.31 b
Fexrtilization/ Irrigation	0.54 a	0.82 a	1.27 a	1.69 a	2.12 a	2.35 a	2.99 a	3.05 a
Average	0.36	0.58	0.85	1.12	1.34	1.49	1.73	1.81

[1/] Treatment means within and between plantation sites with common letter are not significantly different at the .05 level for each date. Statistical mean separations were evaluated by the Duncan method on the Site X Treatment factor from analysis of variance. Site means (N=120) were not significnatly different (0.05 level) for all measurement dates.

Table B-16. Second growing season average[1/] elongation by plantation site treatment and measurement date for the 1981 planted trees. Each value is from 30 completely independent observations per site per treatment.

Plantation Site Treatment	Second Growing Season Elongation by Measurement Date							
	June 16	July 1	July 15	July 30	Aug 12	Aug 27	Sept 10	Sept 29
	meters							
Basher								
Control	0.75 a	1.13 a	1.60 ab	2.13 a	1.19 cd	2.80 a	2.61 d	2.62 d
Irrigation	0.57 c	1.02 bc	1.44 c	1.71 d	2.16 d	2.20 b	2.35 e	2.04 e
Fertilization	0.68 b	1.12 a	1.57 ab	2.11 ab	2.35 bc	2.86 a	2.88 bc	1.75 cd
Fertilization/ Irrigation	0.69 b	1.14 a	1.63 a	2.00 c	2.40 ab	2.86 a	2.99 ab	2.76 cd
Average	0.67	1.10	1.56	1.99	2.27	2.68	2.71	2.54
Morrison								
Control	0.61 c	0.98 bc	1.51 bc	2.06 abc	2.55 ab	2.77 a	2.80 c	2.80 bcd
Irrigation	0.57 c	1.03 b	1.45 c	2.08 abc	2.58 a	2.86 a	2.90 bc	2.89 bc
Fertilization	0.58 c	0.95 c	1.51 abc	2.04 bc	2.42 ab	2.80 a	2.95 bc	2.96 b
Fexrtilization/ Irrigation	0.60 c	0.98 bc	1.59 ab	2.06 abc	2.41 ab	2.92 a	3.14 a	3.20 a
Average	0.59	0.99	1.52	2.06	2.48	2.84	2.95	2.96

[1/] Treatment means within and between plantation sites with common letter are not significantly different at the .05 level for each date. Statistical mean separations were evaluated by the Duncan method on the Site X Treatment factor from analysis of variance. Site means (N=120) were not significnatly different (0.05 level) for all measurement dates, except July 15.

Table B-17. Average[1/] nutrient concentrations in one, two, three and four year old wood samples by plantation site and treatment. These values are from the three replications planted in 1980 and 1981.

Specimen[2/] Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	% oven dry wt.				
One Year Old Wood					
Basher					
Control	0.60a	0.08a	0.27a	0.34abc	0.07a
Irrigation	0.51ab	0.07ab	0.25ab	0.29bc	0.06b
Fertilization	0.50ab	0.06b	0.23b	0.26c	0.06b
Fertilization/Irrigation	0.52ab	0.07ab	0.23b	0.28bc	0.06b
Average	0.53x	0.07x	0.24x	0.29x	0.06x
Morrison					
Control	0.55ab	0.07ab	0.25ab	0.36ab	0.06b
Irrigation	0.48b	0.07ab	0.26ab	0.39a	0.06b
Fertilization	0.50ab	0.06b	0.26ab	0.36ab	0.06b
Fertilization/Irrigation	0.45b	0.06b	0.24ab	0.31abc	0.06b
Average	0.49y	0.07x	0.25x	0.36y	0.06x
Two Year Old Wood					
Basher					
Control	0.34a	0.05a	0.21a	0.19ab	0.04a
Irrigation	0.30ab	0.05a	0.19a	0.16b	0.04a
Fertilization	0.32ab	0.04b	0.21a	0.17ab	0.03b
Fertilization/Irrigation	0.29ab	0.04b	0.21a	0.16b	0.03b
Average	0.31x	0.05x	0.20x	0.17x	0.04x
Morrison					
Control	0.26b	0.04b	0.15b	0.19ab	0.04a
Irrigation	0.27b	0.04b	0.15b	0.21a	0.04a
Fertilization	0.27b	0.03c	0.15b	0.17ab	0.04a
Fertilization/Irrigation	0.26b	0.04b	0.15b	0.18ab	0.04a
Average	0.27y	0.04y	0.15y	0.19x	0.04x
Three Year Old Wood					
Basher					
Control	0.15c	0.04a	0.13a	0.12bc	0.03a
Irrigation	0.19ab	0.03ab	0.14a	0.13ab	0.03a
Fertilization	0.21a	0.03ab	0.14a	0.14a	0.03a
Fertilization/Irrigation	0.22a	0.03ab	0.14a	0.13ab	0.03a
Average	0.19x	0.03x	0.14x	0.13x	0.03x
Morrison					
Control	0.17bc	0.03ab	0.14a	0.11c	0.03a
Irrigation	0.16bc	0.03ab	0.14a	0.12bc	0.03a
Fertilization	0.20a	0.02b	0.14a	0.13ab	0.03a
Fertilization/Irrigation	0.18ab	0.03ab	0.13a	0.12bc	0.03a
Average	0.18x	0.03x	0.13x	0.12y	0.03x

Table B-17. (continued)

Specimen[2/] Plantation Site Treatment	N	P	K	Ca	Mg
	Nutrient				
	- - - - - - - - % oven dry wt. - - - - - - - - -				
Four Year Old Wood					
Basher					
Control	0.12c	0.03a	0.10ab	0.13ab	0.02b
Irrigation	0.12c	0.03a	0.11ab	0.13ab	0.02b
Fertilization	0.17a	0.03a	0.12a	0.14a	0.02b
Fertilization/Irrigation	0.16ab	0.03a	0.12a	0.14a	0.02b
Average	0.14x	0.03x	0.11x	0.13x	0.02x
Morrison					
Control	0.14b	0.02b	0.08b	0.13ab	0.03a
Irrigation	0.13c	0.02b	0.08b	0.12ab	0.03a
Fertilization	0.18a	0.02b	0.09ab	0.14a	0.03a
Fertilization/Irrigation	0.16ab	0.02b	0.09ab	0.12b	0.03a
Average	0.15y	0.02y	0.09y	0.13x	0.03y

[1/] Mean of 6 replications for one and two year old specimens and 3 replications for three year old specimens. Means with a common letter within each nutrient/specimen are not significantly different at the .05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance. Significant Site differences (at 0.05 level) are indicated where the average values have different letters.

[2/] Specimens were collected from the field in October-November and separated from the first 15-45 cm of stem, above ground.

Table B-18. Average[1/] nutrient concentrations in one, two, three and four year old bark samples by plantation site and treatment. These values are from the three replications planted in 1980 and 1981.

Specimen[2/] Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	- - - - - - - - - % oven dry wt. - - - - - - - - -				
One Year Old Bark					
Basher					
Control	1.57b	0.14ab	0.77ab	1.55a	0.20ab
Irrigation	1.52b	0.14ab	0.74ab	1.31b	0.18bc
Fertilization	1.56b	0.15a	0.78a	1.49ab	0.19abc
Fertilization/Irrigation	1.67a	0.15a	0.74ab	1.35b	0.17c
Average	1.58x	0.14x	0.76x	1.42x	0.18x
Morrison					
Control	1.38c	0.13b	0.73ab	1.50ab	0.21a
Irrigation	1.38c	0.13b	0.72b	1.60a	0.19abc
Fertilization	1.42c	0.13b	0.76ab	1.64a	0.19abc
Fertilization/Irrigation	1.43c	0.14ab	0.77ab	1.61a	0.19abc
Average	1.40y	0.13y	0.75x	1.59y	0.19y
Two Year Old Bark					
Basher					
Control	1.27b	0.13a	0.85abc	1.70abc	0.18bc
Irrigation	1.25b	0.13a	0.86ab	1.58bc	0.18bc
Fertilization	1.41a	0.12ab	0.86ab	1.59bc	0.14d
Fertilization/Irrigation	1.45a	0.13a	0.88a	1.52c	0.14d
Average	1.35x	0.13x	0.86x	1.60x	0.16x
Morrison					
Control	1.17b	0.11b	0.73e	1.80ab	0.21a
Irrigation	1.21b	0.11b	0.78d	1.83a	0.20ab
Fertilization	1.46a	0.12ab	0.81cd	1.71abc	0.17c
Fertilization/Irrigation	1.46a	0.12ab	0.83bcd	1.66abc	0.16c
Average	1.33x	0.12y	0.79y	1.75y	0.18y
Three Year Old Bark					
Basher					
Control	0.95b	0.11a	0.74b	1.43b	0.12cd
Irrigation	1.07b	0.11a	0.78ab	1.43b	0.13bc
Fertilization	1.26a	0.11a	0.74b	1.50b	0.10c
Fertilization/Irrigation	1.36a	0.11a	0.77ab	1.51b	0.12bc
Average	1.16x	0.11x	0.76x	1.47x	0.12x
Morrison					
Control	1.05b	0.10b	0.73b	1.44b	0.17a
Irrigation	1.02b	0.10b	0.75ab	1.49b	0.15ab
Fertilization	1.32a	0.10b	0.81a	1.74a	0.14ab
Fertilization/Irrigation	1.10b	0.10b	0.78ab	1.50b	0.14ab
Average	1.12x	0.10y	0.77x	1.54x	0.15y

Table B-18. (continued)

Specimen[2/] Plantation Site Treatment	N	P	K	Ca	Mg
	Nutrient				
	- - - - - - - - - % oven dry wt. - - - - - - - - -				
Four Year Old Bark					
Basher					
Control	0.86b	0.10a	0.71a	1.65ab	0.10b
Irrigation	0.89b	0.09a	0.70a	1.43bc	0.11b
Fertilization	1.10a	0.09a	0.73a	1.72a	0.10b
Fertilization/Irrigation	1.07a	0.09a	0.72a	1.56abc	0.11b
Average	0.98x	0.09x	0.73x	1.59x	0.10x
Morrison					
Control	0.89b	0.09a	0.70a	1.32c	0.14a
Irrigation	0.69c	0.07b	0.71a	1.59abc	0.14a
Fertilization	1.12a	0.09a	0.76a	1.76a	0.13a
Fertilization/Irrigation	1.10a	0.09a	0.77a	1.64ab	0.14a
Average	0.95x	0.08y	0.71x	1.58x	0.13y

[1/] Mean of 6 replications for one and two year old specimens and 3 replications for three year old specimens. Means with a common letter within each nutrient/specimen are not significantly different at the .05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance. Significant Site differences (at 0.05 level) are indicated where the average values have different letters.

[2/] Specimens were collected from the field in October-November and separated from the first 15-45 cm of stem, above ground.

Table B-19. Average[1/] nutrient concentrations in one, two, three and four year old wood/bark composite samples by plantation site and treatment. These values are from the three replications planted in 1980 and 1981.

Specimen[2/] Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	- - - - - - - - % oven dry wt. - - - - - - - -				
One Year Old Wood/Bark Composite					
Basher					
Control	0.91a	0.10a	0.40a	0.77a	0.11a
Irrigation	0.84ab	0.09a	0.38ab	0.62ab	0.10ab
Fertilization	0.85ab	0.09a	0.37ab	0.64ab	0.10ab
Fertilization/Irrigation	0.82ab	0.09a	0.34b	0.59b	0.08c
Average	0.85x	0.09x	0.37x	0.66x	0.10x
Morrison					
Control	0.81ab	0.10a	0.38ab	0.72ab	0.10ab
Irrigation	0.77b	0.09a	0.34b	0.66ab	0.10ab
Fertilization	0.77b	0.09a	0.36ab	0.58b	0.09bc
Fertilization/Irrigation	0.79ab	0.09a	0.37ab	0.65ab	0.09bc
Average	0.78y	0.09x	0.36x	0.65x	0.09y
Two Year Old Wood/Bark Composite					
Basher					
Control	0.49ab	0.07a	0.25bc	0.45bcd	0.06bc
Irrigation	0.50ab	0.07a	0.29ab	0.49abc	0.07b
Fertilization	0.47ab	0.06ab	0.23bc	0.38cd	0.05e
Fertilization/Irrigation	0.46ab	0.06ab	0.22c	0.34d	0.05c
Average	0.48x	0.07x	0.25x	0.41x	0.06x
Morrison					
Control	0.56a	0.07a	0.34a	0.62a	0.09a
Irrigation	0.49ab	0.06ab	0.29ab	0.54ab	0.08ab
Fertilization	0.48ab	0.05b	0.28ab	0.47bcd	0.06bc
Fertilization/Irrigation	0.43b	0.05b	0.26bc	0.38cd	0.05c
Average	0.50x	0.06y	0.29y	0.50y	0.07y
Three Year Old Wood/Bark Composite					
Basher					
Control	0.35c	0.06a	0.32a	0.50a	0.05a
Irrigation	0.39bc	0.06a	0.31a	0.47a	0.05a
Fertilization	0.43abc	0.05ab	0.30a	0.45a	0.05a
Fertilization/Irrigation	0.51a	0.06a	0.29a	0.46a	0.05a
Average	0.30x	0.06x	0.30x	0.47x	0.05x
Morrison					
Control	0.38bc	0.05ab	0.33a	0.52a	0.06a
Irrigation	0.35c	0.05ab	0.31a	0.46a	0.05a
Fertilization	0.47ab	0.04b	0.33a	0.56a	0.06a
Fertilization/Irrigation	0.42bc	0.05ab	0.32a	0.48a	0.05a
Average	0.32x	0.05y	0.32x	0.50y	0.06x

Table B-19. (continued)

Specimen[2/] Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	- - - - - - - - - % oven dry wt. - - - - - - - - -				
Four Year Old Wood/Bark Composite					
Basher					
Control	0.29b	0.05a	0.29ab	0.44ab	0.05a
Irrigation	0.28bc	0.04ab	0.28ab	0.39b	0.05a
Fertilization	0.37a	0.04ab	0.29ab	0.45ab	0.05a
Fertilization/Irrigation	0.39a	0.04ab	0.31a	0.38b	0.05a
Average	0.33x	0.04x	0.29x	0.43x	0.05x
Morrison					
Control	0.26bc	0.04ab	0.26b	0.40ab	0.05a
Irrigation	0.24c	0.03b	0.27b	0.43ab	0.05a
Fertilization	0.37a	0.04ab	0.29ab	0.50a	0.05a
Fertilization/Irrigation	0.31a	0.03b	0.26b	0.43ab	0.05a
Average	0.29y	0.03y	0.27y	0.43x	0.05x

1/ Mean of 6 replications for one and two year old specimens and 3 replications for three year old specimens. Means with a common letter within each nutrient/specimen are not significantly different at the .05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance. Significant Site differences (at 0.05 level) are indicated where the average values have different letters.

2/ Specimens were collected from the field in October-November and separated from the first 15-45 cm of stem, above ground.

Table B-20. Average[1/] nutrient concentrations in one year foliage and fresh litter by plantation site and treatment. Values are from the three replications planted in 1980 and 1981.

Specimen Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	- - - - - - - - - % oven dry wt. - - - - - - - - -				
Foliage[2/]					
Basher					
Control	3.17b	0.27ab	1.62ab	1.29bcd	0.35a
Irrigation	3.21b	0.27ab	1.73a	1.17d	0.32ab
Fertilization	3.36ab	0.27ab	1.72a	1.26cd	0.30ab
Fertilization/Irrigation	3.41ab	0.27ab	1.78a	1.27cd	0.26b
Average	3.29x	0.27x	1.71x	1.25x	0.31x
Morrison					
Control	3.18b	0.23c	1.47b	1.37abc	0.35a
Irrigation	3.13b	0.24bc	1.49b	1.44a	0.34a
Fertilization	3.43ab	0.26abc	1.66ab	1.40ab	0.28b
Fertilization/Irrigation	3.61a	0.28a	1.82a	1.42ab	0.26b
Average	3.34x	0.26y	1.61y	1.41y	0.31x
Litter[2/]					
Basher					
Control	1.99ab	0.10ab	0.80a	1.89b	0.28a
Irrigation	2.18ab	0.10ab	0.72ab	1.72c	0.25abc
Fertilization	1.87b	0.10ab	0.77a	1.81bc	0.27a
Fertilization/Irrigation	2.14ab	0.10ab	0.79a	1.89b	0.25abc
Average	2.03x	0.10x	0.77x	1.83x	0.26x
Morrison					
Control	1.85b	0.09b	0.73ab	1.97ab	0.26ab
Irrigation	2.12ab	0.10ab	0.67b	1.98ab	0.22bc
Fertilization	1.99ab	0.09b	0.76ab	2.11a	0.25abc
Fertilization/Irrigation	2.29a	0.11a	0.72ab	1.96ab	0.20c
Average	2.06x	0.09x	0.72y	2.00y	0.23y

1/ Means of 6 replications and means with a common letter within each nutrient-specimen are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance. Significant site differences (at 0.05 level) are indicated where the average values have different letters.

2/ Foliage samples, about 6 leaves/10 representative trees per site-treatment-replication (total leaves = 60), were collected in late August-early September, before leaf coloration, and from the upper crown. Petioles were removed.

3/ Litter samples of about 60 g were collected from each site-treatment-replication in November, after 99% of the leaves had fallen.

Table B-21. Average[1/] nutrient concentrations in litter[2/] collected in the Spring following first dormant season by plantation site and treatment. Values are from the three replications planted in 1980 and three replications planted in 1981.

Specimen Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	- - - - - - - - - % oven dry wt. - - - - - - - - -				
Basher					
Control	2.01a	0.10ab	0.48b	1.82b	0.11b
Irrigation	2.18bc	0.09b	0.46b	1.80b	0.11b
Fertilization	2.02c	0.11a	0.81a	3.55a	0.33a
Fertilization/Irrigation	2.19bc	0.11a	0.59b	2.44b	0.20b
Average	21.10x	0.10x	0.58x	2.40x	0.19x
Morrison					
Control	2.01c	0.09b	0.58b	1.61b	0.11b
Irrigation	2.63a	0.11a	0.58b	1.89b	0.11b
Fertilization	2.58ab	0.10ab	0.60b	1.79b	0.11b
Fertilization/Irrigation	2.83a	0.12a	0.59b	1.96b	0.10b
Average	2.51y	0.10x	0.59x	1.81y	0.11y

1/ Treatment means within and between plantation sites with a common letter within each nutrient-specimen are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance. Significant site differences (at 0.05 level) are indicated where the average values have different letters.

2/ Litter samples of 60 g were collected from each site-treatment-replication in March, before fertilization amendments.

Table B-22. Average[1/] nutrient concentrations in partly decomposed litter[2/] collected in the late Summer following first dormant season and most of the second growing season by plantation site and treatment. Values are from the three replications planted in 1981.

Specimen Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	- - - - - - - - - % oven dry wt. - - - - - - - - -				
Basher					
Control	0.82c	0.06abc	0.92c	1.48b	0.21abc
Irrigation	0.78c	0.07ab	0.95c	1.48b	0.22abc
Fertilization	1.41a	0.08a	1.39a	1.52b	0.18c
Fertilization/Irrigation	1.36ab	0.07ab	1.43a	1.60b	0.19bc
Average	1.09x	0.07x	1.17x	1.52x	0.20x
Morrison					
Control	0.77c	0.05c	0.90c	1.53b	0.26a
Irrigation	0.92c	0.06abc	1.05c	1.82a	0.24ab
Fertilization	1.00bc	0.07ab	1.12bc	1.96a	0.21abc
Fertilization/Irrigation	1.36ab	0.08a	1.34ab	1.99a	0.21abc
Average	1.01x	0.07x	1.10x	1.83y	0.23y

[1/] Treatment means within and between plantation sites with a common letter within each nutrient-specimen are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance. Significant site differences (at 0.05 level) are indicated where the average values have different letters.

[2/] Litter samples of 60 g were collected from each site-treatment-replication in March, before fertilization amendments.

Table B-23. Average[1/] nutrient concentrations in two year foliage and fresh litter by plantation site and treatment. Values are from the three replications planted in 1980 and three replications planted in 1981.

Specimen Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	- - - - - - - - - % oven dry wt. - - - - - - - - -				
Foliage[2/]					
Basher					
Control	2.40c	0.24bc	1.73ab	1.16bc	0.30b
Irrigation	2.32c	0.24bc	1.83a	1.08c	0.29b
Fertilization	2.86ab	0.23c	1.80ab	1.23ab	0.23c
Fertilization/Irrigation	3.21a	0.27ab	1.82a	1.16bc	0.23c
Average	2.70x	0.24x	1.79x	1.16x	0.26x
Morrison					
Control	2.57bc	0.20d	1.38c	1.28ab	0.35a
Irrigation	2.59bc	0.23c	1.50c	1.34a	0.36a
Fertilization	2.99a	0.25bc	1.65b	1.16bc	0.28b
Fertilization/Irrigation	3.19a	0.28a	1.84a	1.21abc	0.27b
Average	2.83x	0.24x	1.59y	1.25y	0.31y
Litter[3/]					
Basher					
Control	0.87b	0.09ab	1.17bcd	2.01bc	0.32b
Irrigation	0.97b	0.10a	1.13cd	1.83c	0.28b
Fertilization	1.24a	0.08abc	1.39a	2.22a	0.25c
Fertilization/Irrigation	1.30a	0.08abc	1.31ab	2.02bc	0.23c
Average	1.09x	0.08x	1.25x	2.02x	0.27x
Morrison					
Control	0.87b	0.05d	1.05d	1.98c	0.41a
Irrigation	1.00b	0.06cd	1.06d	2.00bc	0.32b
Fertilization	1.03b	0.05d	1.38a	2.30a	0.30b
Fertilization/Irrigation	1.20a	0.07bcd	1.24abc	2.19ab	0.28b
Average	1.02x	0.06y	1.18x	2.12y	0.32y

[1/] Means of 6 replications and means with a common letter within each nutrient-specimen are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance. Significant site differences (at 0.05 level) are indicated where the average values have different letters.

[2/] Foliage samples, about 6 leaves/10 representative trees per site-treatment-replication (total leaves = 60), were collected in late August-early September, before leaf coloration, and from the upper crown. Petioles were removed for analysis.

[3/] Litter samples of about 60 g were collected from each site-treatment-replication in November, after 99% of the leaves had fallen.

Table B-24. Average[1/] nutrient concentrations in litter[2/] collected in the Spring following second dormant season by plantation site and treatment. Values are from the three replications planted in 1980.

Specimen Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	- - - - - - - - - % oven dry wt. - - - - - - - - -				
Basher					
Control	1.40a	0.07a	0.49cd	2.05ab	0.12ab
Irrigation	1.44a	0.07a	0.45d	1.93b	0.13ab
Fertilization	1.67a	0.07a	0.53c	2.27ab	0.11b
Fertilization/Irrigation	1.65a	0.07a	0.48cd	2.05ab	0.12ab
Average	1.54x	0.07x	0.49x	2.07x	0.12x
Morrison					
Control	1.31a	0.07a	0.66ab	2.15ab	0.13ab
Irrigation	1.51a	0.07a	0.60b	2.23ab	0.14a
Fertilization	1.45a	0.07a	0.67a	2.40a	0.13ab
Fertilization/Irrigation	1.63a	0.07a	0.64ab	2.29a	0.14a
Average	1.49x	0.07x	0.64y	2.27y	0.13y

1/ Treatment means within and between plantation sites with a common letter within each nutrient-specimen are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance. Significant site differences (at 0.05 level) are indicated where the average values have different letters.

2/ Litter samples of 60 g were collected from each site-treatment-replication in March, before fertilization amendments, after 99% of leaves had fallen.

Table B-25. Average[1/] nutrient concentrations in partly decomposed litter[2/] collected in late Summer following second dormant season and most of third growing season by plantation site and treatment. Values are from the three replications planted in 1980.

Specimen Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	- - - - - - - - - % oven dry wt. - - - - - - - - -				
Basher					
Control	0.91cde	0.07bc	1.07b	1.79bcd	0.24bc
Irrigation	1.23bcd	0.08bc	1.06b	1.72cd	0.22cd
Fertilization	1.89a	0.11a	1.43a	1.76cd	0.20d
Fertilization/Irrigation	1.50ab	0.09ab	1.08b	2.07abc	0.20d
Average	1.38x	0.09x	1.16x	1.84x	0.22x
Morrison					
Control	0.82de	0.05c	0.98b	1.57d	0.30a
Irrigation	0.77e	0.06c	1.02b	2.10abc	0.30a
Fertilization	1.35bc	0.08bc	1.14ab	2.24a	0.24bc
Fertilization/Irrigation	1.60ab	0.09ab	1.15ab	2.17ab	0.26b
Average	1.13y	0.07y	1.07x	2.02y	0.27y

1/ Treatment means within and between plantation sites with a common letter within each nutrient-specimen are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance. Significant site differences (at 0.05 level) are indicated where the average values have different letters.

2/ Litter samples of 60 g were collected from each site-treatment-replication in August, before leaf fall.

Table B-26. Average[1/] nutrient concentrations in three year foliage and fresh litter by plantation site and treatment. Values are from the three replications planted in 1980 and three replications planted in 1981.

Specimen Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	- - - - - - - - - % oven dry wt. - - - - - - - - -				
Foliage[2/]					
Basher					
Control	2.30c	0.21a	1.72b	1.43a	0.29c
Irrigation	2.49c	0.20a	1.71b	1.32ab	0.26cd
Fertilization	2.89b	0.20a	1.77ab	1.53a	0.24d
Fertilization/Irrigation	3.12ab	0.20a	1.84a	1.51a	0.24d
Average	2.75x	0.20x	1.76x	1.45x	0.26x
Morrison					
Control	2.36c	0.18b	1.59c	1.18b	0.37a
Irrigation	2.36c	0.20a	1.60c	1.35ab	0.33b
Fertilization	3.26a	0.21a	1.75ab	1.52a	0.29c
Fertilization/Irrigation	3.04ab	0.22a	1.72b	1.53a	0.26cd
Average	2.70x	0.20x	1.66y	1.40y	0.31y
Litter[3/]					
Basher					
Control	0.95b	0.09a	0.96d	2.39a	0.24de
Irrigation	1.02b	0.08ab	0.96d	2.10b	0.23de
Fertilization	1.43a	0.08ab	1.14bc	2.51a	0.21ef
Fertilization/Irrigation	1.37a	0.08ab	1.05cd	2.40a	0.20f
Average	1.19x	0.08x	1.03x	2.35x	0.22x
Morrison					
Control	0.98b	0.06c	1.00d	2.04b	0.34a
Irrigation	0.96b	0.07bc	0.99d	2.13b	0.32ab
Fertilization	1.30a	0.06c	1.32a	2.54a	0.29bc
Fertilization/Irrigation	1.42a	0.07bc	1.16b	2.61a	0.25cd
Average	1.17x	0.07y	1.11y	2.33x	0.30y

[1/] Means of 6 replications and means with a common letter within each nutrient-specimen are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance. Significant site differences (at 0.05 level) are indicated where the average values have different letters.

[2/] Foliage samples, about 6 leaves/10 representative trees per site-treatment-replication (total leaves = 60), were collected in late August-early September, before leaf coloration, and from the upper crown. Petioles were removed for analysis.

[3/] Litter samples of about 60 g were collected from each site-treatment-replication in November, after 99% of the leaves had fallen.

Table B-27. Average[1/] nutrient concentrations in four year foliage and fresh litter by plantation site and treatment. Values are from the three replications planted in 1980 and three replications planted in 1981.

Specimen Plantation Site Treatment	Nutrient N	P	K	Ca	Mg
	- - - - - - - - - % oven dry wt. - - - - - - - - -				
Foliage[2/]					
Basher					
Control	2.28c	0.18a	1.75c	1.80ab	0.32ab
Irrigation	2.17c	0.17ab	1.88abc	1.86ab	0.31bc
Fertilization	2.54b	0.18a	2.08a	1.94a	0.28cd
Fertilization/Irrigation	2.57b	0.18a	2.07a	1.85ab	0.27d
Average	2.39x	0.18x	1.94x	1.86x	0.30x
Morrison					
Control	2.28c	0.15c	1.67c	1.46c	0.35ab
Irrigation	2.27c	0.16bc	1.67c	1.63bc	0.35ab
Fertilization	2.87a	0.16bc	1.88abc	1.85ab	0.36a
Fertilization/Irrigation	2.95a	0.16bc	1.95ab	1.86ab	0.34ab
Average	2.59y	0.15y	1.79y	1.70y	0.35y
Litter[3/]					
Basher					
Control	0.95d	0.78bc	0.61d	2.12c	0.17b
Irrigation	0.96d	0.77bc	0.66d	2.37bc	0.18b
Fertilization	1.29c	0.83ab	0.68cd	2.43bc	0.17b
Fertilization/Irrigation	1.22c	0.83ab	0.70cd	2.36bc	0.16b
Average	1.10x	0.80x	0.66x	2.32x	0.17x
Morrison					
Control	1.22c	0.73bc	0.77bc	2.11c	0.20b
Irrigation	1.00d	0.72c	0.83b	2.58b	0.20b
Fertilization	1.77a	0.92a	0.99a	3.28a	0.28a
Fertilization/Irrigation	1.48b	0.92a	0.96a	3.07a	0.30a
Average	1.37y	0.82x	0.88y	2.76y	0.24y

[1/] Means of 6 replications and means with a common letter within each nutrient-specimen are not significantly different at the 0.05 level. Duncan's mean separation method was used on the Site X Treatment factor from analysis of variance. Significant site differences (at 0.05 level) are indicated where the average values have different letters.

[2/] Foliage samples, about 6 leaves/10 representative trees per site-treatment-replication (total leaves = 60), were collected in late August-early September, before leaf coloration, and from the upper crown. Petioles were removed for analysis.

[3/] Litter samples of about 60 g were collected from each site-treatment-replication in November, after 99% of the leaves had fallen.

Table B-28. Average specific gravity values[1/] as a function of management strategy, site, age and component.

Component[2/]		Specific Gravity[3/]			
		Control	Fertilization	Irrigation	Fertilization/ Irrigation
		- - - - - - - - - - Basher Site - - - - - - - - - - - -			
Wood	- 1 year old	0.458aA	0.439aA	0.436aB	0.444aA
	2 year old	0.436aAB	0.415bBC	0.448aA	0.402aC
	3 year old	0.390aA	0.360bA	0.389aA	0.359aA
	4 year old	0.381aAB	0.349bC	0.397aA	0.370aBC
Wood/Bark	- 1 year old	0.433aA	0.424aA	0.400aA	0.414aA
	2 year old	0.415bB	0.412aB	0.438aA	0.402aB
	3 year old	0.398aA	0.371aA	0.409aA	0.376aA
	4 year old	0.382aAB	0.364bB	0.392aA	0.383aAB
Bark	- 1 year old	0.318aA	0.312aA	0.315aA	0.313aA
	2 year old	0.322aA	0.327aA	0.302aB	0.313aAB
	3 year old	0.298aA	0.313aA	0.299bB	0.309aA
	4 year old	0.335aA	0.340aA	0.342aA	0.352aA
		- - - - - - - - - - Morrison Site - - - - - - - - - - - -			
Wood	- 1 year old	0.480aA	0.451aA	0.465aA	0.448aA
	2 year old	0.465aA	0.444aAB	0.448aAB	0.430aB
	3 year old	0.427aA	0.398aA	0.432aA	0.388aA
	4 year old	0.397aA	0.387aA	0.406aA	0.391aA
Wood/Bark	- 1 year old	0.378bA	0.436aA	0.411abA	0.437aA
	2 year old	0.443aA	0.432aAB	0.422aB	0.421aB
	3 year old	0.419aA	0.395aA	0.418aA	0.396aA
	4 year old	0.392aA	0.392aA	0.401aA	0.393aA
Bark	- 1 year old	0.299bA	0.331aA	0.322abA	0.323abA
	2 year old	0.306aA	0.317aA	0.310aA	0.310aA
	3 year old	0.315aA	0.320aA	0.315aA	0.310aA
	4 year old	0.328aA	0.336aA	0.339aA	0.343aA

1/ Differences among management strategies for each site, component and age combination are denoted by upper case letters. Differences between sites for each component, age and management strategy combination are denoted by lower case letters. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

2/ Specific gravity values are based on an average of 9 specimens per plantation establishment year. One year old values are based on replications 4, 5 and 6 and two, three and four year old values are based on replications 1 to 6.

3/ Maximum moisture content method, Smith, D. M. 1955. Maximum Moisture Content Method for Determining Specific Gravity of Small Wood Samples, USDA Forest Service, Forest Products Lab., No. 2014, 8 pp.

Table B-29. Average moisture content values[1/] as a function of management strategy, site, age and component.

Component[2/]		Moisture Content (%)[3/]			
		Control	Fertilization	Irrigation	Fertilization/ Irrigation
		- - - - - - - - - - Basher Site - - - - - - - - - - - -			
Wood	- 1 year old	115.5aAB	119.0aA	120.4aA	107.7aB
	2 year old	108.7aA	109.3aA	115.6aA	114.2aA
	3 year old	95.1aB	89.5aB	109.3aA	101.3aAB
	4 year old	101.1aA	112.9aA	103.5aA	110.2aA
Wood/Bark	- 1 year old	104.9aAB	106.8aAB	112.5aA	97.4bB
	2 year old	110.9aA	107.0aA	116.0aA	112.5aA
	3 year old	97.6aB	99.6aB	111.6aA	103.8aAB
	4 year old	105.9aA	115.6aA	105.7aA	112.4aA
Bark	- 1 year old	87.4aA	93.7aA	93.1aA	91.9aA
	2 year old	97.7aA	98.2aA	99.8aA	101.7aA
	3 year old	103.5aA	109.1aA	106.2aA	106.6aA
	4 year old	108.2aA	114.0aA	107.8aA	109.6aA
		- - - - - - - - - -Morrison Site - - - - - - - - - - - -			
Wood	- 1 year old	116.4aA	103.7aA	118.0aA	109.8aA
	2 year old	106.2aA	107.0aA	108.6aA	107.9aA
	3 year old	93.5aA	91.5aA	93.4bA	93.7aA
	4 year old	87.3bA	83.0bA	89.6bA	84.4bA
Wood/Bark	- 1 year old	104.9aAB	99.3aB	110.0aA	105.3aAB
	2 year old	106.1aA	110.2aA	108.6aA	110.2aA
	3 year old	101.7aA	100.9aA	102.2bA	105.3aA
	4 year old	96.4aA	90.5bA	96.1aA	92.0bA
Bark	- 1 year old	85.7aA	86.4bA	89.2aA	88.7aA
	2 year old	91.7aA	94.2aA	95.8aA	98.2aA
	3 year old	97.9aA	101.2bA	100.1aA	100.4aA
	4 year old	105.4aA	108.4aA	104.5aA	108.0aA

1/ Differences among management strategies for each site, component and age combination are denoted by upper case letters. Differences between sites for each component, age and management strategy combination are denoted by lower case letters. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

2/ Moisture content values are based on an average of 9 specimens per plantation establishment year. One year old values are based on replications 4, 5 and 6 and two, three and four year old values are based on replications 1 to 6.

3/ ASTM D-2016, moisture content = $\frac{\text{wet weight} - \text{oven dry weight}}{\text{oven dry weight}} = 100.$

Table B-30. Average gross heat of combustion values[1/] as a function of management strategy, site, age and component.

Component[2/]		Gross Heat of Combustion (cal/g)[3/]			
		Control	Fertilization	Irrigation	Fertilization/ Irrigation
		- - - - - - - - - - - - Basher Site - - - - - - - - - - - -			
Wood	- 1 year old	4647aA	4631aAB	4608aBC	4584aC
	2 year old	4628aA	4623aA	4645aA	4623aA
	3 year old	4652aA	4617aA	4649aA	4621aA
	4 year old	4596bAB	4575aB	4626aA	4587aB
Wood/Bark	- 1 year old	4725aA	4733aA	4710aA	4723aA
	2 year old	4681aB	4679aB	4713aA	4666aB
	3 year old	4677bA	4661aA	4684aA	4656aA
	4 year old	4612bAB	4649aA	4642aAB	4609aB
Bark	- 1 year old	4851bA	4833bA	4839aA	4829bA
	2 year old	4798aA	4816aA	4813aA	4823aA
	3 year old	4814aA	4735aB	4789bAB	4779aAB
	4 year old	4741bAB	4715bBC	4761aA	4703aC
		- - - - - - - - - - - - Morrison Site - - - - - - - - - - - -			
Wood	- 1 year old	4603bA	4599bA	4604aA	4536aA
	2 year old	4618aA	4627aA	4610bA	4610aA
	3 year old	4641aA	4618aA	4637aA	4626aA
	4 year old	4645aA	4605aAB	4629aA	4571aB
Wood/Bark	- 1 year old	4726aA	4755aA	4694aB	4693aB
	2 year old	4670aA	4661aA	4687aA	4669aA
	3 year old	4721aA	4653aB	4678aB	4659aB
	4 year old	4681aA	4650aB	4660aAB	4618aC
Bark	- 1 year old	4997aA	4928aB	4867aC	4897aBC
	2 year old	4856aA	4833aA	4822aA	4845aA
	3 year old	4877aA	4791aB	4847aA	4794aB
	4 year old	4842aA	4758aBC	4784aB	4736aC

1/ Differences among management strategies for each site, component and age combination are denoted by upper case letters. Differences between sites for each component, age and management strategy combination are denoted by lower case letters. Means with common letters are not significantly different at the 0.05 level as determined by Duncan's mean separation procedure.

2/ Gross heat of combustion values are based on an average of 3 specimens per plantation establishment year. One year old values are based on replications 4, 5 and 6 and two, three and four year old values are based on replications 1 to 6.

3/ ASTM D-2015-66.

Table B-31. Average ash content values[1/] as a function of management strategy, site, age and component.

Component[2/]		Ash Content (% of Oven dry Weight)[3/]			
		Control	Fertilization	Irrigation	Fertilization/ Irrigation
		- - - - - - - - - - - - Basher Site - - - - - - - - - - - -			
Wood	- 1 year old	0.88aA	0.81bA	0.77bA	0.76bA
	2 year old	0.68aA	0.63aA	0.70aA	0.69aA
	3 year old	0.44aA	0.51aA	0.50aA	0.52aA
	4 year old	0.51aA	0.56aA	0.48aA	0.51aA
Wood/Bark	- 1 year old	1.97aB	2.32aA	1.97bB	1.82bB
	2 year old	1.67aA	1.49aAB	1.73aA	1.34aB
	3 year old	1.41aB	1.33aB	1.62aA	1.26aB
	4 year old	1.14aA	1.25aA	1.30aA	1.05aA
Bark	- 1 year old	3.86aB	4.50aA	4.41bA	4.03aB
	2 year old	5.22aA	4.89bA	5.06aA	4.90aA
	3 year old	4.98aA	5.23bA	5.13aA	5.02bA
	4 year old	5.23aA	5.42aA	4.90aA	5.18aA
		- - - - - - - - - - - - Morrison Site - - - - - - - - - - - -			
Wood	- 1 year old	0.79bC	1.12aA	1.00aB	0.80aC
	2 year old	0.68aA	0.53aA	0.81aA	0.80aA
	3 year old	0.42aA	0.43aA	0.44aA	0.46bA
	4 year old	0.35bB	0.46aA	0.46aA	0.44bA
Wood/Bark	- 1 year old	2.37aB	2.52aA	2.00aC	2.48aA
	2 year old	1.82aA	1.32aA	1.82aA	1.36aA
	3 year old	1.46aA	1.37aAB	1.14bBC	1.10bC
	4 year old	0.95bB	1.15aA	1.05bAB	0.94bB
Bark	- 1 year old	4.53aB	4.51aB	4.71aB	5.36aA
	2 year old	5.23aA	5.44aA	5.49aA	5.15aA
	3 year old	4.78aC	5.61aA	5.11aC	5.20aB
	4 year old	5.03aA	5.20aA	4.76aA	5.13aA

1/ Differences among management strategies for each site, component and age combination are denoted by upper case letters. Differences between sites for each component, age and management strategy combination are denoted by lower case letters. Means with common letters are not significnatly different at the 0.05 level as determined by Duncan's mean separation procedure.

2/ Ash content values are based on an average of 3 specimens per plantation establishment year. One year old values are based on replications 4, 5 and 6 and two, three and four year old values are based on replications 1 to 6.

3/ ASTM D-1102, ash content = $\frac{\text{weight ash}}{\text{oven dry weight}} = 100.$

Table B-32. Average extractive content values[1/] as a function of management strategy, site, age and component.

Component[2/]		Extractive Content (% of Oven dry Weight)[3/]			
		Control	Fertilization	Irrigation	Fertilization/ Irrigation
		- - - - - - - - - - - - Basher Site - - - - - - - - - - - -			
Wood	- 1 year old	9.79aA	8.44bC	8.58bC	9.11aB
	2 year old	7.20aA	6.54aA	6.85aA	6.69aA
	3 year old	5.13aB	5.25aAB	5.53aA	5.56aA
	4 year old	5.59aA	5.52aA	5.29aB	5.30aB
Wood/Bark	- 1 year old	21.88aA	22.04bA	19.01bB	19.56bB
	2 year old	15.11aB	13.83aC	16.50aA	13.00aC
	3 year old	13.17bB	12.87aB	14.61aA	12.26aC
	4 year old	11.57aA	10.48bB	10.64aB	10.68aB
Bark	- 1 year old	42.94bA	41.30bC	42.22bB	41.13bC
	2 year old	43.40aA	43.61aA	43.09aA	42.94aA
	3 year old	43.89aA	42.95bB	43.16aAB	43.81aA
	4 year old	41.78aA	41.79aA	42.64aA	42.33aA
		- - - - - - - - - - -Morrison Site - - - - - - - - - -			
Wood	- 1 year old	7.69bB	9.73aA	9.81aA	7.92bB
	2 year old	6.43aA	6.77aA	7.23aA	6.98aA
	3 year old	5.18aA	4.98aA	4.78bA	5.24aA
	4 year old	5.64aA	5.19bB	5.48aA	5.17aB
Wood/Bark	- 1 year old	22.52aA	23.06aA	20.32aB	20.28aB
	2 year old	16.36aA	13.93aBC	15.51aAB	12.77aC
	3 year old	14.50aA	12.36bC	12.85bB	11.59bD
	4 year old	11.51aA	11.25aAB	10.76aBC	10.22bC
Bark	- 1 year old	46.08aA	44.50aC	45.21aB	42.85aD
	2 year old	42.94aA	43.38aA	43.99aA	43.44aA
	3 year old	43.46aA	43.46aA	42.26bB	43.25bA
	4 year old	40.53bA	40.85bA	40.56bA	40.84bA

1/ Differences among management strategies for each site, component and age combination are denoted by upper case letters. Differences between sites for each component, age and management strategy combination are denoted by lower case letters. Means with common letters are not significnatly different at the 0.05 level as determined by Duncan's mean separation procedure.

2/ Extractive content values are based on an average of 6 specimens per plantation establishment year. One year old values are based on replications 4, 5 and 6 and two, three and four year old values are based on replications 1 to 6.

3/ ASTM D-1105-56.

Table B-33. Average holocellulose content values[1/] as a function of management strategy, site, age and component.

Component[2/]		Holocellulose Content (% of Oven dry Weight)[3/]			
		Control	Fertilization	Irrigation	Fertilization/ Irrigation
		- - - - - - - - - - - - Basher Site - - - - - - - - - - -			
Wood	- 1 year old	75.47bB	75.04bB	79.47aA	75.27aB
	2 year old	82.61aA	79.87aA	82.94aA	80.72aA
	3 year old	84.00aA	80.90aB	83.35aA	82.52aAB
	4 year old	84.47aA	82.07aA	83.43aA	82.71aA
Wood/Bark	- 1 year old	63.57aB	61.72bC	64.85aA	64.28aA
	2 year old	72.15aA	73.99aA	68.94aB	73.18aA
	3 year old	72.95aA	74.71aA	70.00bB	73.36aA
	4 year old	74.69aA	76.15aA	76.88aA	75.06aA
Bark	- 1 year old	39.43bB	41.76aA	41.12aA	41.69aA
	2 year old	42.85aA	41.50aA	41.40bA	41.93aA
	3 year old	41.55aA	40.78aA	41.22bA	42.12aA
	4 year old	42.88aA	43.77aA	43.43aA	43.79aA
		- - - - - - - - - - - Morrison Site - - - - - - - - - - -			
Wood	- 1 year old	80.61aA	76.91aB	76.94bB	77.08aB
	2 year old	80.99aA	78.73aA	78.90aA	81.09aA
	3 year old	83.62aA	80.96aA	83.07aA	83.05aA
	4 year old	83.31aA	83.48aA	84.66aA	82.92aA
Wood/Bark	- 1 year old	61.81bB	63.81aA	63.98aA	64.05aA
	2 year old	69.58aA	72.31aA	69.05aA	73.83aA
	3 year old	72.46aB	72.42bB	72.99aAB	74.30aA
	4 year old	74.21aA	75.31aA	76.44aA	75.64aA
Bark	- 1 year old	41.80aAB	42.17aA	40.77aB	41.74aAB
	2 year old	38.41bC	41.28aB	42.84aA	41.20aB
	3 year old	42.03aB	39.82aC	43.72aA	41.14aBC
	4 year old	43.80aA	44.21aA	44.77aA	44.07aA

1/ Differences among management strategies for each site, component and age combination are denoted by upper case letters. Differences between sites for each component, age and management strategy combination are denoted by lower case letters. Means with common letters are not significnatly different at the 0.05 level as determined by Duncan's mean separation procedure.

2/ Holocellulose values are based on an average of 3 specimens per plantation establishment year. One year old values are based on replications 4, 5 and 6 and two, three and four year old values are based on replications 1 to 6.

3/ Acid chlorite method, Browning, B. L. 1967. Methods of Wood Chemistry, Vol. II, Interscience Publishers, New York.

Table B-34. Average alpha-cellulose content values[1/] as a function of management strategy, site, age and component.

Component[2/]		Alpha-Cellulose Content (% of Oven dry Extractive Free Weight)[3/]			
		Control	Fertilization	Irrigation	Fertilization/ Irrigation
		- - - - - - - - - - - Basher Site - - - - - - - - - - -			
Wood	- 1 year old	42.28bAB	40.88bB	42.83bA	38.55bC
	2 year old	43.47aA	42.52aA	43.15aA	43.32bA
	3 year old	44.44aB	43.31bC	44.60aAB	45.14aA
	4 year old	46.63aA	46.39aA	46.06aA	45.99aA
Wood/Bark	- 1 year old	41.08bC	41.47bB	41.89bA	40.91bC
	2 year old	43.22bA	43.47aA	43.05aA	43.40aA
	3 year old	44.51aA	44.50aA	43.70aA	44.06aA
	4 year old	45.84aA	46.37aA	46.24aA	46.57aA
Bark	- 1 year old	39.80bA	37.95bB	38.03aB	36.76bC
	2 year old	43.28aA	41.43aB	41.56aB	40.76aB
	3 year old	42.48aAB	42.24aB	42.38aAB	43.72aA
	4 year old	44.29aA	46.66aA	44.81aA	45.06aA
		- - - - - - - - - - Morrison Site - - - - - - - - - -			
Wood	- 1 year old	43.58aA	43.42aA	43.12aC	43.28aC
	2 year old	44.13aA	42.68aC	43.43aB	44.27aA
	3 year old	44.78aAB	44.14aB	44.34aB	45.08aA
	4 year old	46.56aA	46.96aA	46.99aA	46.46aA
Wood/Bark	- 1 year old	42.86aC	43.35aB	44.54aA	42.27aD
	2 year old	44.53aA	43.72aAB	43.33aB	43.81aAB
	3 year old	45.07aA	43.99aB	43.91aB	44.00aB
	4 year old	46.14aA	46.64aA	46.11aA	46.00bA
Bark	- 1 year old	43.33aA	41.60aA	41.79aA	40.25aA
	2 year old	43.40aA	41.46aA	42.46aA	41.47aA
	3 year old	43.19aA	40.04bB	43.94aA	42.36bA
	4 year old	44.47aA	44.01aA	44.52aA	44.46aA

1/ Differences among management strategies for each site, component and age combination are denoted by upper case letters. Differences between sites for each component, age and management strategy combination are denoted by lower case letters. Means with common letters are not significnatly different at the 0.05 level as determined by Duncan's mean separation procedure.

2/ Alpha-cellulose values are based on an average of 3 specimens per plantation establishment year. One year old values are based on replications 4, 5 and 6 and two, three and four year old values are based on replications 1 to 6.

3/ ASTM D-1103-60.

Table B-35. Average Klason lignin content values[1/] as a function of management strategy, site, age and component.

Component[2/]		Klason Lignin Content (% of Oven dry Weight)[3/]			
		Control	Fertilization	Irrigation	Fertilization/ Irrigation
		- - - - - - - - - - -Basher Site - - - - - - - - - - - -			
Wood	- 1 year old	17.62aA	16.90aA	15.71aA	17.31aA
	2 year old	17.71aA	16.67aAB	15.84aB	16.31aB
	3 year old	16.56aB	17.84aA	18.03aA	16.59aB
	4 year old	16.73aA	16.63aA	16.39aA	15.52aA
Wood/Bark	- 1 year old	19.86aA	18.00aA	19.51aA	20.01aA
	2 year old	17.99aA	18.37aA	18.19aA	18.12aA
	3 year old	18.10aA	18.18aA	17.88aA	17.73aA
	4 year old	16.48aA	17.19aA	16.73aA	16.51aA
Bark	- 1 year old	16.31aA	16.28aA	15.30aB	16.58aA
	2 year old	15.01aA	14.55aA	15.01aA	14.62aA
	3 year old	15.05aA	13.91aA	14.68aA	14.68aA
	4 year old	14.08bAB	13.66aB	14.71bA	14.10aAB
		- - - - - - - - - - Morrison Site - - - - - - - - - - - -			
Wood	- 1 year old	16.26bA	16.24aA	16.01aA	17.36aA
	2 year old	16.19aA	17.40aA	16.72aA	16.27aA
	3 year old	15.87aA	17.03aA	16.80aA	15.60bA
	4 year old	15.91aA	16.30aA	15.49aA	15.00aA
Wood/Bark	- 1 year old	19.28aA	18.48aA	17.86aA	18.71aA
	2 year old	18.24aA	17.92aA	18.08aA	17.67aA
	3 year old	17.65aA	16.62bAB	17.25aAB	16.12bB
	4 year old	16.76aA	17.41aA	17.21aA	16.77aA
Bark	- 1 year old	16.25aB	16.18aB	15.26aC	16.60aA
	2 year old	14.80aA	15.07aA	14.16aA	14.20aA
	3 year old	14.83aAB	14.05aAB	15.65aA	13.29bB
	4 year old	15.10aB	14.23aB	16.87aA	14.67aB

1/ Differences among management strategies for each site, component and age combination are denoted by upper case letters. Differences between sites for each component, age and management strategy combination are denoted by lower case letters. Means with common letters are not significnatly different at the 0.05 level as determined by Duncan's mean separation procedure.

2/ Klason Lignin values are based on an average of 3 specimens per plantation establishment year. One year old values are based on replications 4, 5 and 6 and two, three and four year old values are based on replications 1 to 6.

2/ ASTM D-1106-56.

APPENDIX C

TASK 3

ANALYSIS OF BIOMASS FINANCIAL AND ENERGY DATA

Table C-1. Annual net return per hectare for corn production.

Item	$/ha	10^6kcal/ha
Gross Return	781.18[a]	24.05
Production Costs	(-) 601.19[b]	(-) 6.25
Grain Drying	(-) 70.72[c]	(-) 3.03
Property Tax	(-) 7.85	(-) 1.06
Federal Income Tax	(-) 25.35[d]	(-) 3.69[d]
Total Net	76.06	10.02

[a]Based on 5-year average Pennsylvania farm price, net of hauling and marketing ($\bar{x}$ = $2.87/bu.).

[b]Corn production costs, including management, for minimum tillage, Pa. Dept. of Agr. (1982).

[c]King (1981).

[d]25% of net return after property tax.

Table C-2. Proposed management strategy and salary schedule.

Title	Number[1/] Required	Salary	Fringe[2/] Benefits	Salary Plus Benefits	Total Salary
Management					
Supervisor	1	30,000	6,000	36,000	36,000
Field Manager	1	25,000	5,000	30,000	30,000
Staff					
Clerk I	1	14,000	2,800	16,000	16,800
Clerk II	2	9,000	1,800	10,800	21,600
Foremen					
Nursery-Planning	1	18,000	3,600	21,600	21,600
Silviculturist	3	18,000	3,600	21,600	64,800
Equipment-Harvest	1	18,000	3,600	21,600	21,600
TOTALS	10				212,400

[1/] Personnel requirements were based on the proposed operation of 4 working units of 924 ha each.

[2/] 20% of salary includes payments toward unemployment compensation, hospitalization, life insurance and a pension plan.

Table C-3. Proposed management strategy and energy expenditures for a commercial plantation.

Positions (#)	Weekly[1/] Activity (h)	Yearly Activity (wks)	Total Hours per Year	Net Energy[2/] per Hour (kcal/kg)	Average[3/] Weight (kg/person)	kcal/year
Management-Foremen (7)	54	48	18,144	2.8	74.85	3,802,619.5
Clerks (3)	45	49	6,615	2.8	74.85	1,386,371.70
					TOTAL	5,188,991.2[4/]

[1/] Approximate activity for management under salaried conditions.

[2/] Net kcal/kg/h for men and women undertaking moderate activity levels (4.2 kcal/kg/h) minus those undertaking very light activity (Guthrie, 1975).

[3/] Average kg/person based on average weights for men (90.72 kg) and women (58.97 kg).

[4/] 5,188,991.2 kcal/year for staff divided by 3,696 ha/year under management equals 1,402.95 kcal/ha.

Table C-4. Equipment use for annual biomass harvest and transport between two harvest strategies.

Equipment	Wear-Out Life (h)	Operation Per Year Per Item (h)	Expected Lifetime Per Item (yrs)
Strategy A[1/]			
Tractor (70 hp)	12,000	1,032	11.63
Harvester	5,000	1,032	4.84
Baler	10,000	1,032	9.67
Loader	7,000	1,032	6.78
Unloader	7,000	1,548	4.52
Plant Chipper	10,000	2,000	5.00
Chip Pile Conveyor	10,000	2,064	4.84
Strategy B[2/]			
Harvester/Chipper	7,500	1,032	7.27
Forwarder	7,000	1,032	6.78
Transfer Utility	5,000	1,032	4.84
Unloading Conveyor	10,000	1,548	6.46
Chip Pile Conveyor	10,000	2,064	4.84
A and B			
Fuel Truck	7,000	1,032	6.78
Tractor-Truck	9,000	1,032	8.72
Trailer Van	20,000	1,548	12.92

[1/] Harvest/baling strategy.

[2/] Harvest/chipping strategy.

Table C-5. Strategy A[1/] equipment used in harvest and transport of woody biomass (gross plantation yield of 36 ODt/ha).

Equipment	h/ha	h/yr	ha/yr	units/yr
Tractor (70 hp)	3.34	1,032	309.0	2.99 (3)
Harvester	3.34	1.032	309.0	2.99 (3)
Baler	3.30	1.032	312.7	2.95 (3)
Loader	2.44	1,032	422.9	2.18 (3)
Unloader	2.32	1,548	667.2	1.38 (2)
Plant Chipper (2)	1.74	2,000	1,149.4	0.80 (1)
Chip Pile Conveyor	0.12	2,064	16,591.6	0.06 (1)
Fuel Truck	0.59	1,032	1,740.3	0.53 (1)
Tractor-Truck	3.22	1,032	320.5	2.88 (3)
Trailer Van	4.83	1,548	320.5	2.88 (3)

[1/] Harvest/baling strategy.

Table C-6. Strategy B[1/] equipment used in harvest and transport of woody biomass (gross plantation yield of 36 ODt/ha).

Equipment	h/ha	h/yr	ha/yr	units/yr
Harvester/Chipper	3.22	1,032	320.5	2.88 (3)
Forwarder (2)	6.04	2,064	341.7	2.70 (3)
Transfer Utility	2.90	1,032	355.9	2.60 (3)
Unloading Conveyor	0.67	1,548	2,307.0	0.40 (1)
Chip Pile Conveyor	0.21	2,064	9,971.0	0.09 (1)
Fuel Truck	0.73	1,032	1,413.7	0.65 (1)
Tractor-Truck	5.37	1,032	192.2	4.81 (5)
Trailer Van	8.06	1,548	192.2	4.81 (5)

[1/] Harvest/chipping strategy.

Table C-7. Summary of financial costs per hour for harvest and transport operations (plantation yield of 36 ODt/ha).

Equipment	Total Investment Cost ($)	Fixed Cost per Hour[1/] ($)	Variable Cost per Hour[2/] ($)	Total Cost per Hour ($)
Strategy A[3/]				
Tractor (70 hp)	17,000	2.11	6.51	8.62
Harvester	50,000	12.23	14.78	27.01
Baler	90,000	12.10	22.98	35.08
Loader	50,000	9.35	18.69	28.04
Unloader	50,000	8.32	18.69	27.01
Plant Chipper	32,130	2.48	26.15	28.63
Chip Pile Conveyor	48,510	5.81	5.17	10.99
Strategy B[4/]				
Harvester/Chipper	400,000	71.36	70.87	142.23
Forwarder	87,500	16.43	28.11	44.54
Transfer Utility	50,000	10.47	18.83	29.30
Unloading Conveyor	75,000	9.50	16.97	26.47
Chip Pile Conveyor	48,510	5.81	5.17	10.99
A and B				
Fuel Truck	18,000	3.71	11.61	15.32
Tractor-Truck	76,000	13.32	27.92	41.24
Trailer Van	15,000	1.28	1.91	3.18

1/ Includes depreciation and interest, insurance and shelter costs.

2/ Includes cost for repairs and maintenance, tires, labor and fuel.

3/ Harvest/baling strategy.

4/ Harvest/chipping strategy.

Table C-8. Summary of energy costs for equipment used in harvest and transport operations (gross plantation yield of 36 ODt/ha).

Equipment	Weight (kg)	Embodied Energy[1/] (10^6 kcal)	Fabrication Energy[2/] (10^6 kcal)	Maintenance and Repair Energy[3/] (10^6 kcal)	Fixed Energy per Hour[4/] (10^6 kcal)	Fuel Energy per Hour (10^6 kcal)	Total Energy per Hour (10^6 kcal)
Strategy A[5/]							
Tractor (70 hp)	3,447	0.4	9.9	3.0	0.001	0.122	0.123
Harvestor	680	13.0	23.8	7.4	0.007	0.070	0.077
Baler	10,206	194.2	377.1	87.3	0.055	0.210	0.265
Loader	12,700	242.0	461.4	142.2	0.103	0.377	0.480
Unloader	12,700	242.0	461.4	142.2	0.103	0.377	0.480
Plant Chipper	7,777	147.7	225.4	60.0	0.024	0.550	0.574
Strategy B[6/]							
Harvester/Chipper	33,112	629.5	1,256.8	381.2	0.257	0.629	0.886
Forwarder	13,607	259.2	495.8	152.6	0.110	0.217	0.328
Transfer Utility	4,536	86.9	151.5	60.3	0.051	0.094	0.145
Unloading Conveyor	9,298	176.7	349.5	133.1	0.056	0.131	0.187
Chip Pile Conveyor	7,484	142.4	277.2	106.2	0.045	0.026	0.071
A and B							
Fuel Truck	10,750	204.6	397.7	92.0	0.084	0.010	0.184
Tractor-Truck	6,350	121.6	215.2	68.1	0.038	0.363	0.401
Trailer Van	5,443	104.2	141.9	37.6	0.012	---	0.012

1/ Embodied energy is calculated by multiplying equipment weight by 18,990 kcal/kg for steel, 20,500 kcal/kg for tires and 11,814 kcal/kg for the tractor.

2/ Fabrication energy is calculated by multiplying the weight of the equipment by 3,494 kcal/kg for the tractor, 37,957 kcal/kg for the harvester and tractor-truck and 28,975 kcal/kg for all other equipment.

3/ To establish the energy associated with repair parts, the sum of the embodied and fabrication energy is multiplied by 0.2474 for 70 hp tractor, 0.2021 for harvesters, tractor-trucks, forwarders, loaders, unloaders and conveyors, 0.1527 for fuel trucks, trailer-vans, balers and chippers and 0.2530 for the chip transfer utility.

4/ Fixed energy costs per hour equal the sum of the embodied, fabrication and repair parts energies on a reliable basis (0.82 times sum of embodied and fabricated energy) divided by the hours of lifetime.

5/ Harvest/baling strategy.

6/ Harvest/chipping strategy.

Table C-9. Strategy A[1/] and B[2/]: financial costs of harvest and transport operations (net plantation yield of 32.7 ODt/ha).

Operation	$/ha	$/ODt	%
Strategy A			
Tractor (70 hp)	28.82	0.89	4.7
Harvester	90.26	2.76	14.5
Loader	68.42	2.09	10.9
Baler	115.84	3.54	18.5
Unloader	62.68	1.91	10.0
Plant Chipper (2)	99.64	3.04	15.9
Chip Pile Conveyor	1.36	0.04	0.2
Fuel Truck	9.09	0.28	1.5
Tractor-Truck	132.92	4.06	21.3
Trailer Van	15.39	0.47	2.5
TOTAL	624.42	19.08	100.0
Strategy B			
Harvester/Chipper	458.60	14.00	42.0
Forwarder (2)	269.28	8.22	24.7
Transfer Utility	85.04	2.60	7.8
Unloading Conveyor	17.78	0.55	1.7
Chip Pile Conveyor	2.27	0.07	0.2
Fuel Truck	11.19	0.34	1.0
Tractor-Truck	220.53	6.74	20.2
Trailer Van	25.66	0.78	2.4
TOTAL	1,090.35	33.30	100.0

[1/] Harvest/baling strategy.

[2/] Harvest/chipping strategy.

Table C-10. Strategy A[1/] and B[2/]: energy costs of harvest and transport operations (net plantation yield of 32.7 ODt/ha).

Operation	10^6 kcal/ha	10^6 kcal/ODt	%
Strategy A			
Tractor (70 hp)	0.412	0.013	5.8
Harvester	0.259	0.008	3.6
Baler	0.876	0.027	12.0
Loader	1.171	0.036	16.1
Unloader	1.114	0.034	15.2
Plant Chipper (2)	2.043	0.062	27.7
Chip Pile Conveyor	0.009	0.000	0.0
Fuel Truck	0.109	0.003	1.3
Tractor-Truck	1.295	0.039	17.4
Trailer Van	0.058	0.002	0.9
TOTAL	7.346	0.224	100.0
Strategy B			
Harvester/Chipper	2.857	0.087	36.7
Forwarder (2)	1.980	0.060	25.4
Transfer Utility	0.422	0.013	5.4
Unloading Conveyor	0.126	0.004	1.6
Chip Pile Conveyor	0.015	0.001	0.2
Fuel Truck	0.134	0.004	1.7
Tractor-Truck	2.158	0.066	27.7
Trailer Van	0.096	0.003	1.3
TOTAL	7.788	0.238	100.0

[1/] Harvest/baling strategy.

[2/] Harvest/chipping strategy.

Table C-11. Storage costs for woody biomass.

Strategy	Wet Storage		Dry Storage		Dry (Indoor) Storage	
	$/ODt	10^6 kcal/ODt	$/ODt	10^6 kcal/ODt	$/ODt	10^6 kcal/ODt
A1	8.61	0.056	--	--	--	--
A2	--	--	5.59	0.014	--	--
A3	4.29	0.075	--	--	--	--
A4	4.29	0.075	--	--	--	--
B1	8.90	0.058	--	--	--	--
B2	--	--	5.88	0.016	--	--
B3	8.90	0.058	--	--	--	--
B4	--	--	--	--	3.97	0.039

Table C-12. Drying costs for woody biomass.

	Wet Stored Chips		Dry Stored Chips		Wet (unstored) Chips	
Strategy	$/ODt	10^6 kcal/ODt	$/ODt	10^6 kcal/ODt	$/ODt	10^6 kcal/ODt
A1	--	--	--	--	--	--
A2	--	--	9.14	0.009	--	--
A3	25.02	0.026	--	--	--	--
A4	--	--	--	--	--	--
B1	--	--	--	--	--	--
B2	--	--	9.14	0.009	--	--
B3	15.45	0.016	--	--	--	--
B4	--	--	--	--	11.96	0.012

Table C-13. Biomass costs per ODt by operational stage and distribution by source of inputs.

System #1. Basher control : Harvest/baler/chip : Wet storage

Stage	Total Cost $/ODt	% of Cost From: Capital	Fuel & Materials	Labor	Land
1A. Plantation establishment	9.98	18.4	41.6	39.1	0.9
1B. Plantation maintenance	21.91	1.8	10.0	36.3	51.9
2. Harvest/transport/chip	19.08	50.1	25.9	24.0	0.0
3. Storage	8.60	54.7	21.1	23.9	0.2
Total Cost	59.57	27.7	22.0	31.0	19.3
	10^6kcal/ ODt				
1A. Plantation establishment	0.023	12.2	61.4	0.0	26.5
1B. Plantation maintenance	1.423	0.2	1.9	0.0	97.9
2. Harvest/transport/chip	0.223	14.0	86.0	0.0	0.0
3. Storage	0.056	13.2	81.2	0.0	5.6
Total Cost	1.725	2.6	16.1	0.0	81.3

System #2. Basher control : Harvest/baler/chip : Dry storage

	$/ODt				
1A. Plantation establishment	9.98	18.4	41.6	39.1	0.9
1B. Plantation maintenance	21.91	1.8	10.0	36.3	51.9
2. Harvest/transport/chip	19.08	50.1	25.9	24.0	0.0
3. Storage/dry	14.73	58.9	17.2	23.7	0.1
Total Cost	65.70	31.2	21.0	30.3	17.5
	10^6kcal/ ODt				
1A. Plantation establishment	0.023	12.2	61.4	0.0	26.5
1B. Plantation maintenance	1.423	0.2	1.9	0.0	97.9
2. Harvest/transport/chip	0.223	14.0	86.0	0.0	0.0
3. Storage/dry	0.023	7.7	78.7	0.0	13.6
Total Cost	1.692	2.3	14.8	0.0	82.9

Table C-13. (continued)

System #3. Basher control : Harvest/chipper : Wet storage

Stage	Total Cost $/ODt	% of Cost From: Capital	Fuel & Materials	Labor	Land
1A. Plantation establishment	9.98	18.4	41.6	39.1	0.9
1B. Plantation maintenance	21.91	1.8	10.0	36.3	51.9
2. Harvest/chip/transport	33.30	69.7	13.9	16.4	0.0
3. Storage	8.90	56.0	20.4	23.1	0.5
Total Cost	74.09	41.1	17.3	26.1	15.5
	10^6kcal/ ODt				
1A. Plantation establishment	0.023	12.2	61.4	0.0	26.5
1B. Plantation maintenance	1.423	0.2	1.9	0.0	97.9
2. Harvest/chip/transport	0.238	26.4	73.6	0.0	0.0
3. Storage	0.058	12.7	78.3	0.0	9.0
Total Cost	1.742	4.4	15.0	0.0	80.6

System #4. Basher control : Harvest/chipper : Dry storage

	$/ODt				
1A. Plantation establishment	9.98	18.4	41.6	39.1	0.9
1B. Plantation maintenance	21.91	1.8	10.0	36.3	51.9
2. Harvest/chip/transport	33.30	69.7	13.9	16.4	0.0
3. Storage/dry	15.02	59.6	16.9	23.3	0.3
Total Cost	80.21	42.9	16.9	25.9	14.3
	10^6kcal/ ODt				
1A. Plantation establishment	0.023	12.2	61.4	0.0	26.5
1B. Plantation maintenance	1.423	0.2	1.9	0.0	97.9
2. Harvest/chip/transport	0.238	26.4	73.6	0.0	0.0
3. Storage/dry	0.025	7.0	72.2	0.0	20.8
Total Cost	1.709	4.1	13.7	0.0	82.2

Table C-13. (continued)

System #5. Basher fertilization : Harvest/baler/chip : Wet storage

Phase	Total Cost $/ODt	% of Cost From: Capital	Fuel & Materials	Labor	Land
1A. Plantation establishment	8.30	18.4	41.6	39.1	0.9
1B. Plantation maintenance	18.22	1.8	10.0	36.3	51.9
1C. Plantation fertilization	13.02	5.5	92.6	2.0	0.0
2. Harvest/transport/chip	19.08	50.1	25.9	24.0	0.0
3. Storage	8.60	54.7	21.1	23.9	0.2
Total Cost	67.22	25.1	35.8	24.9	14.2
	10^6kcal/ ODt				
1A. Plantation establishment	0.019	12.2	61.3	0.0	26.5
1B. Plantation maintenance	1.183	0.2	1.9	0.0	97.9
1C. Plantation fertilization	0.319	0.3	99.7	0.0	0.0
2. Harvest/transport/chip	0.223	14.0	86.0	0.0	0.0
3. Storage	0.056	13.2	81.2	0.0	5.6
Total Cost	1.800	2.5	32.7	0.0	64.8

System #6. Basher fertilization : Harvest/baler/chip : Dry storage

	$/ODt				
1A. Plantation establishment	8.30	18.4	41.6	39.1	0.9
1B. Plantation maintenance	18.22	1.8	10.0	36.3	51.9
1C. Plantation fertilization	13.02	5.5	92.6	2.0	0.0
2. Harvest/transport/chip	19.08	50.1	25.9	24.0	0.0
3. Storage/dry	14.73	58.9	17.2	23.7	0.1
Total Cost	73.35	28.4	33.8	24.8	13.0
	10^6kcal/ ODt				
1A. Plantation establishment	0.019	12.2	61.3	0.0	26.5
1B. Plantation maintenance	1.183	0.2	1.9	0.0	97.9
1C. Plantation fertilization	0.319	0.3	99.7	0.0	0.0
2. Harvest/transport/chip	0.223	14.0	86.0	0.0	0.0
3. Storage/dry	0.023	7.7	78.7	0.0	13.6
Total Cost	1.767	2.2	31.8	0.0	66.0

Table C-13. (continued)

System #7. Basher fertilization : Harvest/chipper : Wet storage

Phase	Total Cost $/ODt	% of Cost From: Capital	Fuel & Materials	Labor	Land
1A. Plantation establishment	8.30	18.4	41.6	39.1	0.9
1B. Plantation maintenance	18.22	1.8	10.0	36.3	51.9
1C. Plantation fertilization	13.02	5.5	92.6	2.0	0.0
2. Harvest/chip/transport	33.30	69.7	13.9	16.4	0.0
3. Storage	8.90	56.0	20.4	23.1	0.5
Total Cost	81.74	37.6	29.1	21.6	11.7
	10^6kcal/ ODt				
1A. Plantation establishment	0.019	12.2	61.3	0.0	26.5
1B. Plantation maintenance	1.183	0.2	1.9	0.0	97.9
1C. Plantation fertilization	0.319	0.3	99.7	0.0	0.0
2. Harvest/chip/transport	0.238	26.4	73.6	0.0	0.0
3. Storage	0.058	12.7	78.3	0.0	9.0
Total Cost	1.817	4.2	31.5	0.0	64.3

System #8. Basher fertilization : Harvest/chipper : Dry storage

	$/ODt				
1A. Plantation establishment	8.30	18.4	41.6	39.1	0.9
1B. Plantation maintenance	18.22	1.8	10.0	36.3	51.9
1C. Plantation fertilization	13.02	5.5	92.6	2.0	0.0
2. Harvest/chip/transport	33.30	69.7	13.9	16.4	0.0
3. Storage/dry	15.02	59.6	16.9	23.3	0.3
Total Cost	87.86	39.5	27.9	21.7	10.9
	10^6kcal/ ODt				
1A. Plantation establishment	0.019	12.2	61.3	0.0	26.5
1B. Plantation maintenance	1.183	0.2	1.9	0.0	97.9
1C. Plantation fertilization	0.319	0.3	99.7	0.0	0.0
2. Harvest/chip/transpor	0.238	26.4	73.6	0.0	0.0
3. Storage/dry	0.025	7.0	72.2	0.0	20.8
Total Cost	1.784	4.0	30.6	0.0	65.5

Table C-14. Operational parameters and financial costs (1981 dollars) of potential conversion strategies for woody biomass.

Type of Process	Product	Capacity	Woody Biomass Feedstock	Fixed and Capital cost ($)	Operation and Maintenance cost ($)
Multischeme[1/] Chemical Plant	Ethanol Furfural Phenol	94.62×10^6 ℓ/yr 34.02×10^6 kg/yr 23.59×10^6 kg/yr	1361 ODt/d	10.26×10^6/yr	0.807×10^6/yr
Hydrolysis-Fermentation[2/]	Ethanol	13.21×10^6 ℓ/yr	1.853×10^6 t/yr	0.775/ℓ	0.381/ℓ
Gasification[3/]	Medium Btu gas	1.79×10^{12} kcal/yr	1600 ODt/d	$3.89/10^6$ kcal/yr	$3.47/10^6$ kcal/yr
Liquefaction[4/]	Wood oil	5268 bbl/d 7.70×10^9 kcal/d	2722 ODt/d	$10.36/10^6$ kcal	$8.17/10^6$ kcal/yr
Pyrolysis[4/]	Oil, char	99×10^3 ℓ/d, 6.98 t/d	454 ODt/d	$3.73/10^6$ kcal	$6.90/10^6$ kcal/yr
Combustion[5/] Turbine Generation	Electricity	100-MW	oil gas	0.044/kwh 0.044/kwh	0.03/kwh 0.03/kwh
Wood-fired Power Plant	Electricity	50-MW	219×10^3 ODt/yr	0.037/kwh	0.03/kwh

[1/] U.S.D.A. Forest Service (1976).

[2/] Wright and d'Agencourt (1984).

[3/] Desrosiers (1979).

[4/] Schooley *et al*. (1978).

[5/] Skelton *et al*. (1982).

Table C-15. Comparison of forest biomass conversion techniques.

Conversion Technique	Conversion Products	Estimated Energy Content of Products (Gross Heat of Combustion)	Yield (%) of energy Content in Wood
Direct Incineration[1/]	Biomass/Heat	18.6 - 22.1 MJ/kg	65-84
Pyrolysis[2/]	Char	27.9 MJ/kg	35-47
	Condensate	22.1 - 32.5 MJ/kg	20-35
	Non-condensible gas	11.2 - 28.7 MJ/kg	18-28
Gasification[3/]	Gas Mixture	3.7 - 7.0 MJ/kg	60-80
	Methanol	20.1 MJ/kg	30-50
Liquefaction[4/]	Liquid	36.5 MJ/kg	30-53
Hydrolysis/Fermentation	Ethanol	29.7 MJ/kg	46[5/]

[1/] Walters, et. al. 1980, Goldstein 1979 and Schooley, et al. 1978.

[2/] Klass 1976, Riley and Smith 1977, Walters, et al. 1980, Goldstein 1979, Bliss and Blake 1977, and Aton 1979.

[3/] SERI 1979, Katzen 1975; Schooley, et al. 1978, Alich and Inman 1974, Walters, et al. 1980, USDA 1976.

[4/] Goldstein 1979 and Schooley, et al. 1978.

[5/] Calculated assuming a conversion efficiency of wood to ethanol of 30% by weight and a higher heating value of 19.4 MJ/kg of woody biomass.

Table C-16. Estimated electrical and ethanol conversion potential by management strategy and site for the first rotation.

Management Strategy	Gross Biomass Yield ODt/ha	Biomass Yield at Conversion Site ODt/ha[1/]	Total Tree GHC cal/g[2/]	Electrical Energy Output 10^3 kwh/ha[3/]	Ethanol Yield ℓ/ha[4/]
Basher -					
Control	35.34	31.81	4620.2	48.32	6033
Irrigation	32.65	29.39	4648.7	45.00	5574
Fertilization	42.51	38.26	4607.1	57.93	7256
Fertilization/ Irrigation	43.04	38.74	4607.7	58.67	7347
Morrison -					
Control	31.59	28.43	4680.0	43.87	5392
Irrigation	33.95	30.56	4656.9	46.85	5796
Fertilization	38.20	34.38	4634.7	52.44	6520
Fertilization/ Irrigation	41.11	37.00	4602.8	55.94	7017

1/ Assumes a harvesting efficiency of 90% (gross biomass yield x 0.90 = yield at conversion site).

2/ Total tree gross heat of combustion (GHC) = (.7 x GHC for wood) + (.15 x GHC for bark) + (.15 x GHC for wood/bark). Four year old GHC values were used for wood, bark and wood/bark (branches) components by management strategy and site.

3/ Accounts for losses due to: 1) moisture (672 cal/g of water) at 20% moisture content, 2) hydrogen combustion (367 cal/g OD wood) and 3) stack gases (383 cal/g OD wood) (Koch, 1972). Also assumes electrical production efficiency of 35% (Babcock and Wilcox Co. 1975) and 3413 BTU = 1 kwh.

4/ Assumes 15% of biomass yield at conversion site is converted into ethanol (Neeman, 1984) and 1264.3 ℓ of ethanol are derived from each ODt of EtOH and a heating value of 5613 kcal/ℓ (Energy from Biological Processes 1980).

Table C-17. Net financial analysis (including plant costs) for producing electricity by management strategy and site for the first rotation.

Management Strategy	Biomass Yield at Conversion Site ODt/ha [1/]	Financial Costs: Production $/ODt [2/]	Financial Costs: Total $/ha [3/]	Electricity Output 10^3 kwh/ha	Electrical Input Costs: $/kwh [4/]	Electrical Input Costs: Total $/kwh [5/]	Net $/kwh [6/]
Basher -							
Control	31.81	28.71	2450.32	48.32	0.051	0.118	-.072
Irrigation	29.39	96.40	4253.32	45.00	0.095	0.162	-.116
Fertilization	38.26	35.60	3210.78	57.93	0.055	0.122	-.076
Fertilization/ Irrigation	38.74	84.71	5153.58	58.67	0.088	0.155	-.109
Morrison -							
Control	28.43	32.12	2286.91	43.87	0.052	0.119	-.073
Irrigation	30.56	103.62	4643.29	46.85	0.099	0.166	-.120
Fertilization	34.38	44.10	3177.40	52.44	0.061	0.128	-.082
Fertilization/ Irrigation	37.00	101.86	5556.66	55.94	0.099	0.166	-.120

1/ Assumes a harvesting efficiency of 90% (gross biomass yield x 0.90 = yield at conversion site).

2/ From Table 3-6.

3/ Production financial costs plus $48.32/ODt for harvest, transportation, drying and storage (Strategy B2). Multiply total $/ODt by biomass yield at conversion site to produce total $/ha.

4/ Divide $/ha by kwh/ha.

5/ Assumes plant costs of $0.067/kwh for a wood fired power plant (Skelton et al. 1982)

6/ Subtract total electrical input cost ($/kwh) from an assumed residential consumer price of $0.046/kwh.

Table C-18. Net financial analysis (including plant costs) for producing ethanol by management strategy and site for the first rotation.

Management Strategy	Biomass Yield at Conversion Plant ODt/ha[1/]	Financial Costs		Ethanol Output ℓ/ha	Ethanol Input Costs		
		Production $/ODt[2/]	Total $/ha[3/]		$/ℓ[4/]	Total $/ℓ[5/]	Net $/ℓ[6/]
Basher -							
Control	31.81	28.71	1520.20	6033	0.25	0.49	-.04
Irrigation	29.39	96.40	3393.96	5574	0.61	0.85	-.40
Fertilization	38.26	35.60	2092.06	7256	0.29	0.53	-.08
Fertilization/ Irrigation	38.74	84.71	4020.82	7347	0.55	0.79	-.34
Morrison -							
Control	28.43	32.12	1455.62	5392	0.27	0.51	-.06
Irrigation	30.56	103.62	3749.71	5796	0.65	0.89	-.44
Fertilization	34.38	44.10	2172.13	6520	0.33	0.57	-.12
Fertilization/ Irrigation	37.00	101.86	4474.78	7017	0.64	0.88	-.43

1/ Assumes a harvesting efficiency of 90% (gross biomass yield x 0.90 = yield at conversion site).

2/ From Table 3-6.

3/ Production financial costs plus $19.08/ODt for harvest and transportation (Strategy A). Multiply total $/ODt by biomass yield at conversion site to produce total $/ha.

4/ Divide $/ha by ℓ/ha.

5/ Assumes plant costs of $0.24/ℓ of ethanol (Neeman 1984).

6/ Subtract total ethanol input cost ($/ℓ) from a list price for fermented ethanol of $0.45/ℓ (Chemical Marketing Reporter, May 13, 1985).

Table C-19. Net energy analysis (excluding plant costs) for producing electricity by management strategy and site for the first rotation.

Management Strategy	Biomass Yield at Conversion Plant ODt/ha[1/]	Energy Inputs: Production 10^6 kcal/ODt[2/]	Energy Inputs: Total 10^6 kcal/ha[3/]	Total Tree GHC cal/g[4/]	Electrical Output 10^6 kcal/ha[5/]	Net 10^6 kcal/ha[6/]
Basher -						
Control	31.81	1.302	49.783	4620.2	41.559	- 8.224
Irrigation	29.39	1.570	53.872	4648.7	38.703	-15.169
Fertilization	38.26	1.372	62.555	4607.1	49.824	-12.731
Fertilization/ Irrigation	38.74	1.477	67.408	4607.7	50.461	-16.947
Morrison -						
Control	28.43	1.456	48.871	4680.0	37.732	-11.139
Irrigation	30.56	1.517	54.397	4656.9	40.295	-14.102
Fertilization	34.38	1.608	64.325	4634.7	45.102	-19.223
Fertilization/ Irrigation	37.00	1.628	69.967	4602.8	48.113	-21.854

1/ Assumes a harvesting efficiency of 90% (gross biomass yield x 0.90 = yield at conversion site).

2/ From Table 3-6.

3/ Production energy costs plus 0.263 x 10^6 kcal/ODt for harvest, transit, drying and storage (Strategy B2). Multiply total 10^6 kcal/ODt by biomass yield at conversion site to produce total 10^6 kcal/ha.

4/ Total tree gross heat of combustion (GHC) = (.7 x GHC for wood) + (.15 x GHC for bark) = (.15 x GHC for wood/bark). From year old GHC values were used for wood, bark and wood/bark (branches) components by management strategy and site.

5/ Electricity output (kwh/ha) from Table C-3 x 860.076 = electricity output (kcal/ha). Accounts for losses due to: 1) moisture (672 cal/g of water) at 20% moisture content, 2) hydrogen combustion (367 cal/g OD wood) and 3) stack gases (383 cal/g OD wood) (Koch, 1972). Also assumes electrical production efficiency of 35% (Babcock and Wilcox Co. 1975) and 3413 BTU = 1 kwh.

6/ Subtract total energy input (kcal/ha) from electricity output (kcal/ha).

Table C-20. Net energy analysis (excluding plant costs) for producing ethanol by management strategy and site for the first rotation.

Management Strategy	Biomass Yield at Conversion Plant ODt/ha[1/]	Energy Inputs: Production 10^6/kcal/ODt[2/]	Energy Inputs: Total 10^6kcal/ha[3/]	Ethanol Yield ℓ/ha[4/]	Ethanol Output 10^6 kcal/ha[5/]	Net 10^6 kcal/ha[6/]
Basher -						
Control	31.81	1.302	48.542	6033	33.851	-14.691
Irrigation	29.39	1.570	52.726	5574	31.276	-21.450
Fertilization	38.26	1.372	61.063	7256	40.713	-20.350
Fertilization/ Irrigation	38.74	1.477	65.897	7347	41.224	-24.673
Morrison -						
Control	28.43	1.456	47.762	5392	30.255	-17.507
Irrigation	30.56	1.517	53.205	5796	32.521	-20.684
Fertilization	34.38	1.608	62.984	6520	36.584	-26.400
Fertilization/ Irrigation	37.00	1.628	68.524	7017	39.372	-29.152

1/ Assumes a harvesting efficiency of 90% (gross biomass yield x 0.90 = yield at conversion site).

2/ From Table 3-6.

3/ Production energy costs plus 0.224 10^6 kcal/ODt for harvest and transportation (Strategy A). Multiply total 10^6 kcal/ODt by biomass yield at conversion site to produce total 10^6 kcal/ha.

4/ Assumes 15% of biomass yield at conversion site is converted into ethanol (Neenam, 1984) and 1264.3 ℓ of ethanol are derived from each ODt of EtOH and a heating value of 5613 kcal/ℓ (Energy from Biological Processes 1980).

5/ Multiply ℓ/ha by 5611 kcal/ℓ (84,300 BTU/gal) for ethanol.

6/ Subtract total energy input (kcal/ha) from ethanol output (kcal/ha).

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80. J. C. Dula, 31150 South Needy Road, Canby, OR 97013
81. T. H. Ellis, Director, Southern Forest Experiment Station, T-10210 U.S. Postal Service Bldg., 701 Loyola Ave., New Orleans, LA 70113
82. J. Erickson, Forest Products Laboratory, 1 Gifford Pinchot Drive, Madison, WI 53705
83. R. L. Ethington, Director, Pacific Northwest Forest and Range Experiment Station, 319 S. W. Pine Street, P. O. Box 3623, Portland, OR 97232
84. A. S. Fege, Northeastern Forest Experiment Station, 370 Reed Road, Broomall, PA 19008
85. P. Felker, College of Agriculture, Texas A&I University, Kingsville, TX 78363
86. J. A. Fisher, Fiber Fuels Institute, 310 Cedar Street, St. Paul, MN 55101
87. G. J. Foley, Office of Environmental Process and Effects Research, U.S. Environmental Protection Agency, 401 M Street, SW, RD-682, Washington, DC 20460
88. Pat Fox, Bonneville Power Administration, P. O. Box 3621, Routing EPG, Portland, OR 97208
89. D. S. Frederick, School of Forest Resources, North Carolina State University, Raleigh, NC 17650
90. M. S. Fry, Miles W. Fry & Son, Inc., Frysville, R.D. 3, Ephrata, PA 17522
91. W. A. Geyer, Department of Forestry, Kansas State University, Manhattan, KS 66506
92. Alberto Goetzl, National Forest Products Association, 1619 Massachusetts Ave., NW, Washington, DC 20036
93. C. R. Goldman, Professor of Limnology, Director of Tahoe Research Group, Division of Environmental Studies, University of California, Davis, CA 94616
94-98. S. C. Grado, School of Forest Resources, Pennsylvania State University, University Park, PA 16802

99. S. Hale, Energy/Development International, 1015 18th Street, N.W., Suite 802, Washington, DC 20036
100. R. B. Hall, Forestry Department, 251 Bessey Hall, Iowa State University, Ames, IA 50011
101. R. A. Hann, Director, North Central Forest Experiment Station, 1992 Folwell Avenue, St. Paul, MN 55108
102. J. W. Hanover, Department of Forestry, Michigan State University, East Lansing, MI 48824
103. E. A. Hansen, USDA Forest Service, Forestry Sciences Laboratory, P. O. Box 898, Rhinelander, WI 54501
104. W. Heckrodt, Kimberly Clark, W-5409 Mielke Road, Menasha, WI 54952
105. P. E. Heilman, Western Washington Research and Extension Center, Puyallup, WA 98371
106. B. Holloman, New York State Energy Research and Development Authority, Agency bldg. #2, Empire State Plaza, Albany, NY 12223
107-111. C. Hornicsar, School of Forest Resources, Pennsylvania State University, University Park, PA 16802
112. J. W. Huckabee, Project Manager, Environmental Assessment Department, Electric Power Research Institute, 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94303
113. J. G. Isebrands, USDA Forest Service, Forestry Sciences Laboratory, P. O. Box 898, Rhinelander, WI 54501
114. George Y. Jordy, Director, Office of Program Analysis, Office of Energy Research, ER-30, G-226, U.S. Department of Energy, Washington, DC 20545
115. R. C. Kellison, Director, North Carolina State University Cooperative Programs, School of Forest Resources, North Carolina State University, Raleigh, NC 27650
116. K. Kilpatrick, Forest Resources, Univversity of Idaho, Moscow, ID 83843
117. F. A. Koomanoff, Director, Carbon Dioxide Research Division, Office of Energy Research, Room J-309, ER-12, U.S. Department of Energy, Washington, DC 20545
118. S. L. Krugman, USDA Forest Service, P. O. Box 2417, Room 811, RPE, Washington, DC 20013
119. F. Laing, Botany Department, University of Vermont, Burlington, VT 05401
120. L. E. Lassen, Director, Intermountain Forest and Range Experiment Station, Forest Service Bldg., 324 25th Street, Ogden, UT 84401
121. R. Loose, Director, Office of Renewable Technology, CE 52, Department of Energy, 1000 Independence Avenue, Washington, DC 20585
122-126. B. E. Lord, School of Forest Resources, Pennsylvania State University, University Park, PA 16802
127. D. Lothner, USDA Forest Service, North Central Forest Experiment Station, P. O. Box 338, 515 West First Street, Duluth, MN 55801
128. C. M. Loveless, Director, Rocky Mountain Forest and Range Experiment Station, 240 W. Prospect Street, Fort Collins, CO 80526
129. Helen McCammon, Director, Ecological Research Division, Office of Health and Environmental Research, Office of Energy Research, MS-E201, ER-75, Room E-233, Department of Energy, Washington, DC 20545

130. C. M. McKell, Vice President Research, Plant Resources Institute, 417 Wakara Way, Salt Lake City, UT 84108
131. R. McKenna, Meridian Corp., 5113 Leesburg Pike, Suite 700, Falls Church, VA 22041
132. R. Miller, Mt. Jefferson Farms, P. O. Box 12395, Salem, OR 97309
133. C. P. Mitchell, Department of Forestry, University of Aberdeen, St. Machar Drive, Old Aberdeen, Scotland, AB9 2UU
134. M. J. Morin, HRAMOR Nursery, 515 Ninth Street, Manistee, MI 49660
135. W. K. Murphey, USDA, Cooperative State Research Service, 14th & Independence Ave., SW, Washington, DC 20250
136. J. C. Nautiyal, Faculty of Forestry, University of Toronto, 203 College Street, Toronto, Ontario, Canada M5S 1A1
137. E. A. Nelson, Westvaco, Timberlands Division, Box 458, Wickliffe, KY 42087
138. R. A. O'Connell, Biomass Energy Technology Division, CE 321, U.S. Department of Energy, Washington, DC 20545
139. William S. Osburn, Jr., Ecological Research Division, Office of Health and Environmental Research, Office of Energy Research, MS-E201, EV-33, Room F-216, Department of Energy, Washington, DC 20545
140. P. E. Pope, Department of Forestry and Natural Resources, Forestry Building, Purdue University, West Lafayette, IN 47907
141. Robert Rabson, Office of Basic Energy Sciences, ER-17, U.S. Department of Energy, Washington, DC 20545
142. Irwin Remson, Department of Applied Earth Sciences, Stanford University, Stanford, CA 94305
143. D. C. Rinebolt, Coalition of Northeastern Governors, 400 North Capitol Street, Washington, DC 20001
144. D. L. Rockwood, School of Forest Resources and Conservation, 118 Newins-Ziegler Hall, University of Florida, Gainesville, FL 32611
145. G. F. Schiefelbein, Biomass Program Office, Pacific Northwest Laboratory, P. O. Box 999, Richland, WA 99352
146. J. Sesco, Director, Southeastern Forest Experiment Station, 200 Weaver Blvd., P. O. Box 2680, Asheville, NC 28802
147-156. S. Sprague, Biomass Energy Technology Division, Department of Energy, Forrestal Building, Washington, DC 20585
157. K. Steinbeck, School of Forest Research, University of Georgia, Athens, GA 30602
158. R. J. Stern, Director, Office of Environmental Compliance, MS PE-25, FORRESTAL, U.S. Department of Energy, 1000 Independence Avenue, SW, Washington, DC 20585
159. R. Stettler, College of Forest Resources, University of Washington, Seattle, WA 98195
160-164. C. H. Strauss, School of Forest Resources, Pennsylvania State University, University Park, PA 16802
165-169. G. L. Stimely, School of Forest Resources, Pennsylvania State University, University Park, PA 16802
170-174. L. R. Stover, School of Forest Resources, Pennsylvania State University, University Park, PA 16802
175. C. G. Tauer, Department of Forestry, 013 South Ag. Hall, Oklahoma State University, Stillwater, OK 74078

176. J. M. Vasievich, USDA Forest Service, Southeastern Forest Experiment Station, P. O. Box 12254, Research Triangle Park, NC 27709
177. Robert L. Watters, Ecological Research Division, Office of Health and Environmental Research, Office of Energy Research, MS-E201, ER-75, Room F-226, Department of Energy, Washington, DC 20545
178. Leonard H. Weinstein, Program Director of Environmental Biology, Cornell University, Boyce Thompson Institute for Plant Research, Ithaca, NY 14853
179. E. H. White, College of Environmental Science and Forestry, State University of New York, Syracuse Campus, Syracuse, NY 13210
180. C. D. Whitesell, USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, 1151 Punchbowl Street, Room 323, Honolulu, HI 96813
181. Raymond G. Wilhour, Chief, Air Pollution Effects Branch, Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency, 200 SW 35th Street, Corvallis, OR 97330
182. Frank J. Wobber, Ecological Research Division, Office of Health and Environmental Research, Office of Energy Research, MS-E201, Department of Energy, Washington, DC 20545
183. M. Gordon Wolman, The Johns Hopkins University, Department of Geography and Environmental Engineering, Baltimore, MD 21218
184. G. Wyckoff, The Institute of Paper Chemistry, P. O. Box 1093, Appleton, WI 54912
185. J. I. Zerbe, USDA Forest Service, Forest Products Laboratory, P. O. Box 5130, Madison, WI 53705
186. L. Zsuffa, Faculty of Forestry, University of Toronto, Toronto, Ontario, Canada M5S 1A1
187. Office of Assistant Manager for Energy Research and Development, Oak Ridge Operations, P. O. Box E, U.S. Department of Energy, Oak Ridge, TN 37831

188-214. Technical Information Center, Oak Ridge, TN 37831