THE EFFECT OF CLIMATE ON THE GROWTH OF SALIX SPECIES IN AN EXPERIMENTAL ENERGY PLANTATION ENVIRONMENT

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BY

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Abstract

The spatially diverse and often unsettled nature of the summer weather of insular Newfoundland suggests that the influence of climate on biomass production should be taken into consideration when examining potential sites for wood energy plantations. The growth of shoot height and base diameter of three willow (*Salix*) species in an experimental energy plantation environment at Pasadena, Newfoundland (49°01'N latitude, 57°36'W longitude) was examined during the 1985 growing season. *S.viminalis* (clone number 0683, Sweden) was found to be the most successful clone, achieving a final mean shoot height of 209 cm and a final mean shoot base diameter of 1.49 cm. *Salix purpurea* (clone number 077, Sweden) and *S.alba* (clone number 5023, Romania) shoots attained final mean heights of 183 cm and 180 cm respectively, and final mean base diameters of 1.07 cm and 1.44 cm respectively. The three species were significantly different in their final mean height and base diameter attainment.

The height and base diameter of *S.viminalis*, *S.purpurea* and *S.alba* clones was recorded on a weekly basis between June 10 and October 7, 1985. The seasonal pattern of shoot height and base diameter growth of *S.viminalis* and *S.alba* clones was effectively explained by second-order polynomial regression equations (multiple $r^2 \geq 98\%$). The seasonal pattern of *S.purpurea* shoot height growth was also described by a quadratic equation whereas base diameter growth during the 1985 growing season was described by a cubic or third-order polynomial regression equation.

Total shoot height of the three species was recorded daily between June 21 and August 14, 1985 and climatic variables at the experimental plantation site were monitored simultaneously. Real and derived climatic variables recorded the current day and the previous day were tested for entry into multiple regression models with the daily shoot height increment change of each of the three species as the dependent variable. Maximum air temperature and the hours of daylight of the current day accounted for 69%, 59% and 55% of the variance in daily height growth of *S.purpurea*, *S.viminalis* and *S.alba* shoots respectively. Values of evapotranspiration determined for the previous day from measurements of net radiation and modeled values of the amount of water in the root zone, accounted for a further 10% and 3% of the variablility in daily height growth of *S.viminalis* and *S.purpurea* shoots respectively.

It is concluded from the results of this study that maximum biomass production of the three species examined will be realised at plantation sites where the climate of the growing season enables maximum photosynthetic efficiency via high inputs of solar energy and the avoidance of water deficit conditions.

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This thesis is dedicated to my parents, for without their blind belief in their daughter's love of the woods and their unfailing support throughout the years, I might still be selling Space Age Shelving.

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Chapter 1
Introduction

1.1. Wood energy plantation forestry

The concept of wood energy plantations was first introduced by Szego and Kemp in 1973 (Anderson *et al*, 1983) in response to the world oil 'shortage'. The concept attempted to address the apparent under-utilization of photosynthetic energy available from solar radiation to create wood biomass, particularly in countries possessing few fossil energy deposits (Siren, 1980). Potential uses of biomass from energy plantations include wood for domestic fuel, for electric power generation and for conversion to liquid and gas fuels.

Wood energy plantations or "short-rotation forests" (Fege, 1981) consist of genetically improved, fast growing trees, which are intensively cultivated and subject to harvests every two to ten years. Planting density and plantation size may vary according to availability of land, choice of mechanization for harvesting, and tree species grown. Hardwood tree species are most suited to this type [illegible] forestry due to their ability to re-sprout, which is necessary for the plantation to persist through repeated harvests. Deciduous species that have been studied and used for energy plantations in temperate climates include sycamore, maple, birch, ash, sweetgum, black locust, alder, poplar and willow (Fege, 1981).

The obvious goal of short rotation forestry is the maximization of biomass production. This is attempted via the breeding of genetic clones for high productivity and the matching of tree species and genetic clone to site. Preparation of the site through the removal of existing vegetation and amelioration of the soil prior to planting is necessary to ensure maximum growth and productivity. The selection of an optimal planting density for the clone and the site is also important. The determination of nutrient requirements of the trees and choice of the method for application of these nutrients will insure that growth is not reduced due to nutrient stress. In addition, the choice of the most beneficial cultivation practices and the selection of methods of weed and pest control are undertaken to enable maximum survival of trees in the wood energy plantation.

Cloning is the creation of genetic replicas of trees by vegetative propagation. Trees which possess desired traits such as superior biomass characteristics, frost hardiness, pest resistance, etc. may therefore be selected and reproduced. For species such as willow and poplar this is accomplished by the planting of stem cuttings which will root and grow into separate plants (Anderson *et al*, 1983). Poplar and willow species also hybridize readily so that two species both possessing superior qualities may be bred together to produce interspecific hybrids with ideal characteristics (ibid). Clones may then be matched to specific sites where they might produce best under the existing environmental conditions.

The choice of site is very important in short rotation forestry. Existing plantations are generally located on abandoned agricultural lands in Canada and the United States, and on peatlands that have been exploited for fuel in Sweden, Finland and Ireland (Anderson *et al*, 1983). The availability of land is an obvious restriction in the selection of sites for wood energy plantations. Soil properties considered important for tree growth include structure, texture, chemical composition, aeration and moisture and nutrient availability (Fege, 1981). The roots of plants must be able to easily penetrate the soil, respire and find available nutrients and water (Olsson *et al*, 1984). Amelioration of the soil prior to planting is usually necessary in energy plantation forestry if maximum growth is expected to occur. Measures employed include the removal of existing vegetation, plowing and cultivation to modify the soil structure, and the application of lime and fertilizers (Fege[illegible]981).

Type of planting stock is dependent on the tree species cultivated. For those species which reproduce vegetatively, shoot cuttings measuring 15 to 25 cm in length are planted vertically, either flush with the ground or with at least one bud above the soil surface (Food and Agriculture Organisation, 1979). The relatively narrow spacing of trees in wood energy plantations has made conventional forestry planting machinery obsolete. Although modifications to forestry and agricultural planting machinery have been made, the development of planting machinery specifically geared towards short rotation forestry is necessary (Fege, 1981). Planting of bare root seedlings and containerized seedlings also occurs, but it is considered more expensive than the planting of hardwood cuttings.

Planting density is an important component of energy plantation forestry. The optimal density will be dependent on the species grown and the methods of planting, cultivation and harvesting (Anderson *et al*, 1983). Densely planted trees (i.e. 0.3 m by 0.3 m) will form a closed canopy rapidly, inhibiting the growth of weeds. However, if mechanical soil tending is to take place, the spacing should be at least 3 m by 3 m (ibid). The control of weed growth is particularly important during the first few years after planting so that the roots are able to firmly establish themselves. The removal of competing vegetation will enable the young plants to make full use of the available light, moisture and nutrients. If mechanical tending of the soil is undertaken on a regular basis, the growth of weeds between the rows will be controlled. In more densely planted plantations where mechanical tending is not feasible, the application of herbicides may be necessary for the control of weed species.

The intensive nature of short rotation forestry is likely to result in a higher demand for nutrients per unit time than more traditional forestry practices (Anderson *et al*, 1983). Repeated harvesting results in the depletion of nutrients on plantation sites due to the regular removal of the existing vegetation and the subsequent leaching of nutrients. Knowledge of a tree species' specific demand for nutrients during growth is required in order to achieve optimal growth in an energy plantation environment (Fege, 1981). This type of information might be gained from laboratory experiments examining the rate of ion uptake by roots, the degrees and rates of nutrient utilization for different shoot ages and seasons, and the distribution of nutrients within the various plant components (ibid).

There is however, no extensive literature on the nutrient requirements of different species for their optimal growth (Anderson *et al*, 1983). Nitrogen, phosphorus and potassium are commonly used in wood energy plantations to enrich soils (Fege, 1981). High concentrations of nitrogen in the leaves of poplar have been found necessary for active growth to occur (Anderson *et al*, 1983). The monitoring of nitrogen during the growing season is necessary as it can be leached away or may become bound to other materials in the soil rendering it unavailable to the roots for uptake. Timing of applications, application rate and relative concentrations of fertilizers will be dependent on the plantation site and the requirements of the species grown.

The examination of the susceptibility of various clones to pests and diseases is necessary if optimal production is to be achieved in wood energy plantation forestry. A single high yielding clone is typically planted over a large area, and one herbivorous insect species could theoretically destroy a plantation if preventive measures were not employed. Breeding of clones for resistance to particular insects and diseases that are known hazards is the most effective method of protection. Insecticides and fungicides may also be used although the potential environmental hazards should be carefully examined before their employment. Herbivorous mammals also pose a threat to wood energy plantations. *Salix spp.* (willow) energy plantations in Sweden experience large production losses due to browsing moose and minor losses to deer, rabbits and voles (Christersson and von Fircks, 1984). Preventative measures such as the fencing in of plantations or the use of chemical repellents are considered extremely expensive, and environmentally objectionable in the case of chemical use. The breeding and selection of clones that are more browse-resistant than others may alleviate potential losses due to animal pests.

Intensively managed, short rotation forests in temperate climates have been developed relatively recently and most of the yields reported in the literature to date are from areas where clones are being tested for production under natural conditions. Yield projections are therefore generally made from small research plots (Fege, 1981). Reported yields of *Populus spp.* (poplar) clones in Canada have ranged from 5 to 19 tonnes of dry matter per hectare per year (t DM/ha/yr) (ibid). Sweden has achieved impressive results using *Salix* clones in experimental wood energy plantations. During the first growing season (season of planting) stem biomass yields are relatively low at 1 to 3 tonnes of dry matter per hectare per year. Yields following the year of establishment range between 10 to 20 t DM/ha/yr depending on regional climate and the intensity of management. The best yield attained in Sweden was 36 t DM/ha/yr in 1985, when the plantation was irrigated and fertilized regularly (Perttu and Lindroth, 1986).

1.2. Plant growth and climate

The selection of plantation site in wood energy production must take into consideration the effect of the local climatic conditions on the growth of the plants and the subsequent production of viable biomass. The vegetative growth of plants is the result of a combination of physical and physiological processes which create plant constituents from carbon dioxide, oxygen, water and nutrients.

The process of photosynthesis results in the conversion of absorbed light into chemical energy used in the reduction of carbon-dioxide to form carbohydrates, and the uptake and transport of water, minerals and assimilates (Gaastra, 1963). The quality of light that produces an optimal rate of photosynthesis is species specific. Shade tolerant species are adapted to maximize their rate of photosynthesis when exposed to less than full sunlight, whereas shade intolerant species will experience maximum rates of photosynthesis when exposed to full light (Jones, 1983). Photosynthesis is one of the most temperature sensitive aspects of plant growth and there is a broad optimum response range for photosynthesis in relation to temperature for different species (ibid). Generally, photosynthetic rate increases with temperature to an optimum, but it declines at high temperatures. The water status of the plant also affects the rate of photosynthesis, which declines with decreasing water potential (ibid).

The process of respiration results in the formation of high energy compounds from the oxidation of carbohydrates to carbon-dioxide and water. The energy created by the respiration process is used for the growth and synthesis of new cell constituents and for the maintenance of existing cell structure (Jones, 1983). The amount of energy available for growth, synthesis and maintenance is directly dependent on the availability of carbohydrates created by photosynthesis, and thus is indirectly subject to the same environmental effects. Respiration rate is highly sensitive to changes in temperature, and increases with increasing temperature (ibid).

Water comprises as much as 50% of the fresh weight of woody plants and therefore is necessary to maintain the basic structure of plants (Jones, 1983). A maintenance of water potential within the plant is necessary for growth to occur, as cell expansion and division are dependent on turgor pressure created by the concentration of water in plant cells (Jones, 1983). The water status of a plant will also affect the activities of enzymes needed for chemical reactions which will in turn affect the rates of synthesis and degradation of cell constituents (ibid). An adequate supply of water is also required for the metabolism of carbon and nitrogen and the synthesis of proteins. Water is the solvent in which gases, minerals and other solutes enter plant cells and are transported between cells and plant organs. It is also the reactant or substrate in many biochemical processes and is fundamental in the process of photosynthesis (Raven *et al*, 1981).

Transpiration involves the loss of water vapour from the plant and is dependent on the supply of energy and the vapour pressure gradient between the surface where evaporation is occurring and the air (Kramer, 1983). It is the dominant process in plant-water relations as it is this evaporative demand that results in the movement of water into the roots, through the plant via the xylem and out through the stomata, the pores in leaves and stems through which gases pass, as water vapour. Approximately 95% of water that enters a plant is lost via transpiration while only the remaining 5% is used for metabolism and growth (ibid). When the transpirational demand from the atmosphere exceeds the rate of supply that a plant is able to maintain, the water content, turgor, and total plant water potential is reduced and stress conditions result. Water stress conditions typically cause the closure of the stomata, which inhibits the uptake of carbon-dioxide from the atmosphere and in turn limits the rate of photosynthesis (Eckersten, 1985). Water stress in plants leads to an overall reduction in growth due to the limitations it imposes on all physiological and biochemical activities which are dependent on an adequate water potential. High rates of transpiration may have positive effects in that the rate of absorption of minerals may be increased by the increased speed and quantity of water being moved from the roots through the plant (Kramer, 1983).

Translocation is the process by which the carbohydrates created by photosynthesis are transported via the phloem, from the leaves to various sites within the plant where they may be stored or used for growth (Raven *et al*, 1981). Although the mechanics of translocation are not fully understood, it is thought that photosynthates are transported on a source-to-sink basis, where the sources are the leaves and storage areas, and the sinks are those plant parts that are unable to meet their own nutritional needs to enable growth. Translocation of assimilates from leaves is known to be reduced in water stress conditions for some plant species, although the process does not appear to be as sensitive to water deficits as photosynthesis (Kramer, 1983). The concentration of assimilates transported during water deficit situations is generally lower than during non-stress conditions. Wardlaw (1968) attributed this to the effect of the lowered activities of both the source and the sink areas during water shortages, rather than the reduced ability of the conducting system to transport materials.

1.3. The effect of climate on growth in wood energy plantations

Perttu and Lindroth (1986) state that in Sweden, the single most influential climatic factor in determining production in energy plantation forestry in northern latitudes is air temperature. This is due to it's control over the length of the growing season. The regions of Sweden considered suitable for energy plantation forestry are those which possess a minimum of 1100 degree days (threshold value of 5 °C) (Perttu and Lindroth, 1986).

Air temperatures below 0 °C during the growing season pose a potential threat to production in energy plantations, particularly if the low temperatures result in the formation of ice crystals in the tissues of the plants (Christersson and von Fircks, 1984). Frost occurring within the growing season typically results in the death of the youngest parts of the plants where the active meristems are located. This suggests that elongation of the stem would be severely restricted by the freezing of plant tissue, not only due to the death of meristems but also due to the destruction of plant parts necessary for photosynthesis to occur (ibid). *Salix* species studied under laboratory conditions in Sweden have shown frost damage when exposed to temperatures between -2 and -3 °C.

In Sweden, the effect of climate on biomass production in *Salix spp.* energy plantations has been investigated through the modelling of growth processes as a function of climatic variables. The aim of the research is to provide accurate predictive models so that potential productivity for various regions may be estimated for years with good, average and poor weather conditions (Eckersten *et al*, 1983).

The models are based on those previously developed for agricultural crops, for although the plants are woody perennials, the horizontally homogeneous nature of plantations make them most similar to agricultural ecosystems (Eckersten, 1985). The model proposed and tested by Eckersten (1985) is based on predicting biomass in tonnes of dry matter per hectare as a function of photosynthesis, a water-growth factor and a temperature function. Daily potential photosynthesis is estimated from incident light (400 - 700 nm) using the Michaelis-Menten equation. The effect of plant water status on the rate of photosynthesis is taken into account due to its effect on the stomatal and mesophyll resistances, and the subsequent control imposed on the flow of carbon di-oxide into the plant. The water-growth factor is derived from a complex plant water model (Kowalik and Eckersten, 1984), which simulates the movement of water through the plant using continuously recorded values of air temperature and relative humidity, solar radiation, soil water potential and an empirically established value for stomatal resistance. The temperature function is set at zero for days with mean daily temperatures below 5 °C and increases linearly to a value of one at 15 °. The temperature function remains constant at one for mean daily temperatures above 15 °C.

The above model was tested against measured values of dry matter accumulation in first season shoots of *Salix viminalis* clone 082 grown in an experimental energy plantation at the Swedish Energy Forestry Project's Studvik research station (58° 48' N, 17° 24' E) (Nilsson and Ericsson, 1986). The trees were planted at a density of 9 plants per square meter and were fertilized and irrigated during the 1981 growing season (Eckersten, 1985). The simulated values of growth agreed well with the measured values and Eckersten (1985) concludes that for *Salix* shoots in their first and second seasons of growth, the model appears to account for the most essential processes involved in controlling growth. It was also concluded that the effect of temperature and plant water status on photosynthesis should be examined further, especially under field conditions. One limitation of the model is that it has not yet been shown to be applicable to all clones, species, plantation sites and different ages of shoots.

1.4. Wood energy plantation research in Newfoundland

The Newfoundland Forest Research Centre of the Canadian Forestry Service began research into the potential of *Salix spp.* as an energy forestry crop in 1981 (Robertson, 1984). More than 140 *Salix* clones were acquired from European, American and Canadian sources and established at nursery sites in the eastern and western regions of the island of Newfoundland. The monitoring of clones grown in test plots at these sites took place in an effort to identify those clones which might perform best under the environmental conditions in Newfoundland.

Yield estimates from the nursery trials show that the potential of *Salix* species for energy plantation forestry in Newfoundland is very promising. Various clones in their third season of growth produced yields of between 2 and 27 t DM/ha/year when planted at a density of 30,000 stems per hectare (Robertson, personal communication, 1986).

The spatially diverse and often unsettled nature of the summer weather of insular Newfoundland suggests that the bioclimatological control of biomass production should be closely examined if maximum yields are expected. This particular study examines the growth of three *Salix* clones at the Pasadena nursery site in western Newfoundland during the 1985 growing season. Measurements of shoot height and base diameter were recorded weekly throughout the growing season, and daily during the period of maximum growth. Daily growth increments were examined with respect to climatic variables recorded at the site in an effort to determine the effect of climate on growth of the three species under consideration.

Chapter 2

Site Description and Data Collection

2.1. Site Description

The study took place at the Newfoundland Forest Research Centre's nursery at Pasadena, Newfoundland (49° 01' N latitude, 57° 36' W longitude). Pasadena is located in the western portion of the island of Newfoundland (see Figure 1-1) at an elevation of 35 meters and is at the western edge of the "Central lowlands" climatic zone of Newfoundland (Banfield, 1981). Total annual precipitation within this zone is near 1200 mm, with an average of 27 % falling as snow. Mean seasonal total precipitation during the growing season (May to September) at the Deer Lake climatological station (49° 10' N latitude, 57° 26' W latitude)[1] is near 400 mm. Mean potential evapotranspiration (50% probability) within the region during the growing season is 350 to 400 mm (Agriculture Canada, 1976). The Climatic Moisture Index, the ratio of seasonal precipitation to the amount of water used by a crop under conditions of unlimited water supply, is 80 to 100 % (ibid). The average date of the last spring frost (0° C) at the Deer Lake climatological station is June 8 and the average date of the first autumn frost September 14 (Hemmerick and Kendall, 1972). The average length of frost free conditions lasts 97 days. Summers within this zone are generally warm, with maximum temperatures often reaching 25-32 °C when the air flow is from a SW-SE direction. The annual average degree days above 5 °C is 1200. The central lowlands zone is considered the least windy and foggy climatic zone on the island (Banfield, 1981).

Agriculture Canada (personal communication, 1985) has classified the soil in the area as an Orthic Humo-Ferric Podzol. The parent material is a gravel/pebble fluvial deposit, derived from red sandstone, gray siltstone and granite rocks. The texture of the soil is predominantly a sandy

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[1] This climatological station is distinguished from the "Deer Lake Airport" climatological station located at 49° 13' N latitude, 57° 24' W latitude

loam, and in an undisturbed state, the soil is strongly acidic ($pH < 4.6$). The soils within the nursery have been enriched by years of cultivation, with fertilizers being applied at least once a year for the last 5 years.

Approximately one-half of the nursery has been designated for the cultivation of willows, the total area comprising approximately one-third of a hectare. The layout of this portion of the nursery is shown in Figure 2-2. The bulk of the original *Salix* clones were obtained from the Long Ashton Research Station, Bristol, England, the Swedish University of Agricultural Sciences, Uppsala, Sweden, and the Montreal Botanic Garden (Robertson, 1982). The species of clones represent collections from throughout Europe and Eastern North America.

During the 1985 growing season all fields were fertilized during the last week of May and the last week of August at a rate of 3 kg/ha with Ammonium nitrate (31-0-0, 100 kg/ha), Phosphoric acid (0-20-0, 60 kg/ha) and Nitrate of potash (0-0-62, 180 kg/ha). The area between rows was weeded regularly by Roto-tiller or by hand with a hoe. Infrequent occurrences of Spiny Elm caterpillar, the larval form of the Mourning Cloak butterfly (*Nymphalis antiopa* (Linnaeus)), the Spotted Tussock moth (*Halysidota maculata* (Harris)) and an unknown caterpillar were treated by hand spraying with Malathion ($C_{10}H_{19}O_6PS_2$). Malathion is an organophosphate which is generally non-phytotoxic, and it has brief to moderate persistence (Worthing, 1979).

2.2. Data Collection

2.2.1. Growth Measurements

The willows studied during the 1985 growing season were located in the field labelled "A" in Figure 2-2. Approximately 2000 cuttings from plants established at Pasadena in 1982 were planted in rows in field "A" during May of 1983, with a spacing of 25 cm^2. The shoots of the plants were cut to ground level on May 7, 1985.

An area of field "A" was chosen where three species of *Salix* had been planted in adjacent rows (see Figure 2-2) and thirty stools of each species were randomly selected and tagged on May 12, 1985. The three species examined in this study were *Salix purpurea* (clone number 077) and *S.viminalis* (clone number 0683), both acquired from Sweden, and *S.alba* (clone number 5023, Romania), acquired from the Montreal Botanic Garden.

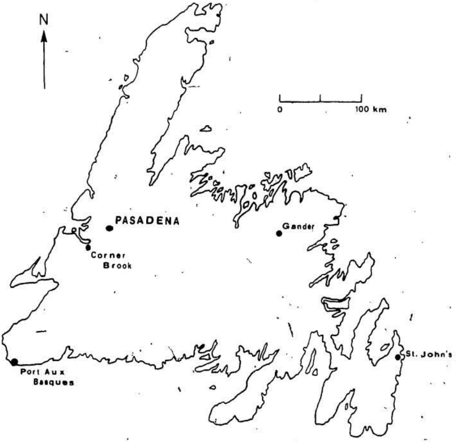

Figure 2-1: Map of the island of Newfoundland showing the location of the Pasadena nursery site.

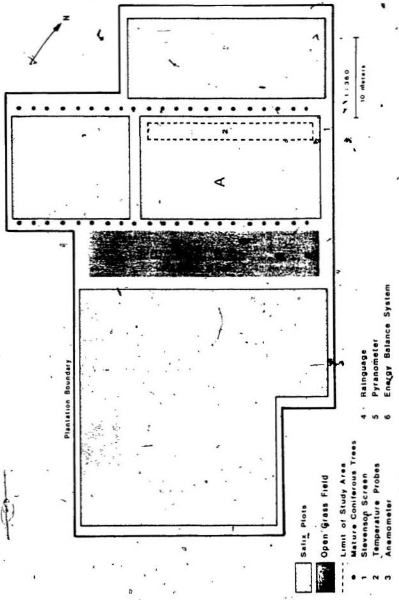

Figure 2-2: Diagram of the experimental energy plantation at Pasadena, Newfoundland.

Research conducted by the Swedish Energy Forestry Project (Nilsson and Eckersten, 1986) indicates that the dry weight of willow stems is related to measurements of shoot height and base diameter through the following equation:

$$M_s = P \cdot D^2 \cdot H \tag{2.1}$$

where; M_s is the dry weight of the stem,
P is a parameter,
D is the shoot base diameter,
and H is the shoot height.

Shoot height and base diameter were therefore chosen as indicator variables of growth in this study. Height of the longest shoot on each of the ninety stools was measured to the nearest 0.5 cm with a standard tape measure and recorded on a weekly basis from June 10 to October 7. Diameter of the same shoot at approximately 0.5 cm above where it emerged from the stool (henceforth referred to as base diameter) was measured to the nearest 0.1 mm using Venier calipers and was also recorded on a weekly basis throughout the growing season. Height and base diameter were recorded three times daily, at 06:00, 14:00 and 22:00 NDST (Newfoundland Daylight Saving Time), from June 20 to August 14. Measurements of the ninety shoots took approximately one hour to complete.

2.2.2. Meteorological Measurements

A Stevenson screen was located at "1" in Figure 2-2 and contained a Casella thermohygrograph, maximum and minimum thermometers and wet- and dry-bulb thermometers (see Figure 2-3). The screen height was at approximately 1.5 m above the ground. Air temperature was recorded continuously by the thermohygrograph from May 7 until October 7, 1985; however, the humidity arm of the thermohygrograph was inoperable for most of the study period and therefore this data was not used. Measurements of maximum air temperature from a mercury-in-glass thermometer and minimum air temperature from an alcohol minimum thermometer were recorded at 06:00, 14:00 and 22:00 NDST daily from June 20 to August 14. The wet- and dry-bulb thermometers were mercury-in-glass thermometers, and the wet-bulb was kept moist by a wick and reservoir apparatus. Wet-and dry-bulb temperatures were also recorded at 06:00, 14:00 and 22:00 NDST daily from June 20 to August 14.

Figure 2-3: Photograph of the contents of the Stevenson screen.

Three YSI temperature probes were established in each of the three species' rows at "2" in Figure 2-2, and were tested for accuracy prior to the study period. The probes were buried at 10, 20 and 30 cm below the surface in each of the three rows. Instantaneous readings of soil temperature to the nearest 0.5 ° C were displayed by a YSI model 42SC tele-thermometer and recorded at 06:00, 14:00 and 22:00 hours daily from June 20 to August 14.

The remainder of the climatic sensors were located in field "B" in which grass seed planted early in June gradually grew throughout the study period. A Science Associates anemometer (see Figure 2-4) was located at "3" in Figure 2-2. Wind speed in miles per hour at 3.0 metres above the ground was recorded continuously throughout the study period by an Esterline-Angus recorder (see Figure 2-5). Wind direction was recorded but not used in this study due to the suspected un-reliability of the wind vane and the potential influence of local and micro scale shelter. The Pasadena nursery is sheltered on a local scale by the foothills of the Long Range Mountains to the east and on a micro scale by mature forest trees around the fields as shown in Figure 2-6. Precipitation was measured by a standard AES type 'B' daily rain gauge located at "4" in Figure

2-2. The rim of the gauge was 40 cm above the ground surface and the circular orifice measured 11.3 cm in diameter. Rain was funneled into a clear plastic graduate and was recorded to the nearest 0.25 mm at 06:00, 14:00 and 22:00 NDST from June 20 to August 14.

Figure 2-4: Photograph of the Science Associates anemometer.

A Matrix Inc. radiometer was located at "5" and measured incoming shortwave solar radiation (0.30 - 3.00 μm) at 2.0 m above the grassed surface of the field. Signals from the radiometer, in millivolts, were recorded continuously on a strip-chart recorder. Occasional malfunctions of the recorder meant that it was operational for only part of the study period. The dates of complete solar radiation data collected are listed in Appendix A.

An energy balance measurement system (see Figure 2-7), developed and constructed by Dr. J.H. McCaughey of the Department of Geography at Queen's University, was being field tested at Pasadena and was located at "6" in Figure 2-2. The system was not in operation continuously throughout the study period and the energy balance of the site was not derived due to the incomplete nature of the data set.

This energy balance measurement system consisted of a Reversing Temperature Difference Measurement System (RTDMS), four five junction copper-constantin thermopiles for the measurement of wet- and dry-bulb temperatures, a Middelton model CN-1 net pyrradiometer, a

Figure 2-5: Photograph of the Esterline-Angus recorder.

Figure 2-6: Photograph of the micro-scale shelter of the Pasadena nursery site.

Sierra model RG 2501 tipping bucket rain gauge and a Campbell Scientific CR7 data system (McCaughey, 1981, 1986). The measurements of wet- and dry-bulb temperature and net radiation as recorded by the energy balance measurement system were made available for this research. The dates of data collected by the system and used in this study are listed in Appendix A.

Figure 2-7: Photograph of the energy balance measurement system.[2]

The psychrometer "cart" of the energy balance system shown in Figure 2-8 consisted of wet- and dry-bulb sensors held within a styrofoam cylinder which was covered with reflective aluminized tape to shield the sensors from the effects of radiation (McCaughey, 1986). An aspiration fan was fixed to each radiation shield and the water was fed continuously through the cotton wick to the wet-bulb sensor from the reservoir. Two psychrometer carts were fixed to the elevator type RTDMS, at 1.0 and 3.5 meters above the ground. The RTDMS interchanged the position of the psychrometers each half hour (ibid). The signals from the sensors of the pyschrometer unit attached to the left side of the rail were sampled by the CR7 data logging system every thirty seconds and converted into hourly average values of wet- and dry-bulb air temperatures in degrees Celsius. The hourly averages given were the result of the signals recorded in the preceeding hour.

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[2] Note: only wet- and dry-bulb temperatures and net radiation data from this system were used in the study.

Figure 2-8: Photograph of the pyschrometer units of the energy balance measurement system.

The Middelton net pyrradiometer was fixed at a height of 1.5 m above the ground surface and was continuously purged with nitrogen. The signals from the net pyrradiometer were sampled every 30 seconds by the CR7 data system and converted into hourly average values of net radiation in Watts per square meter. The hourly averages recorded were then calculated from signals received in the preceeding hour.

2.3. Published Data

2.3.1. Deer Lake Climatological Station Data

The Atmospheric Environment Service's "Deer Lake" station is located at 49 ° 10' N latitude, 57 ° 26' W latitude, on the northeast shore of Deer Lake at an elevation of 11 m, approximately 25 km to the northeast of the Pasadena nursery site. It is part of the Atmospheric Environment Service's climate station network and was chosen over the "Deer Lake Airport" climatological station referred to in Section 2.1 as it was the closest station to the Pasadena nursery site. Also, the proximity and relative position of Deer Lake to both the Pasadena nursery site and the "Deer Lake" climatological station meant that any moderating effects of the lake would be experienced simultaneously at both sites. The station records of daily mean, maximum and minimum air temperatures and daily precipitation during the study period were used in certain aspects of this study.

2.3.2. Daylength Data

The length of time between sunrise and sunset in hours, for latitude 49° N, were taken from Agriculture Canada's (1974), "Selected Tables and Conversions Used in Agrometeorology and Related Fields". The daily values are the output of a computer program (Robertson and Russelo, 1968) where sunrise and sunset are assumed to occur when the centre of the sun is 50 minutes below the horizon.

Chapter 3

Data Analysis Procedures

This chapter deals with the conversion of the willow growth and climatic variables collected into values used in the analysis of the data.

3.1. Conversion of raw data to daily values

3.1.1. Growth Measurements

Total shoot height and base diameter, of the longest shoot on each of thirty stools of each of the three species, were averaged for measurements recorded weekly throughout the growing season and for measurements recorded daily at 06:00 hours between June 20 and August 14, 1985.

The daily height and base diameter increment change in centimeters, for the 56 day measurement period were calculated by subtracting the day's measurement of total shoot height and base diameter on each of the ninety stools at 06:00 hours, from the following day's measurements at 06:00 hours. Mean height and base diameter increment change for each species was calculated by averaging the thirty values of height and base diameter increment change for each time interval.

3.1.2. Air and soil temperatures

The hourly average values of dry-bulb air temperature, recorded by the CR7 data logger system of the energy balance system, were averaged to give values of mean daily air temperature from 07:00 hours to 06:00 hours the proceeding day. When the energy balance system was not operational, mean daily air temperature was calculated from hourly values read from the chart of the Casella thermohygrograph, from 06:00 hours to 05:00 hours the proceeding day.

Values of maximum and minimum air temperature between 06:00 hours and 06:00 hours the proceeding day were recorded. Also, the daily range in air temperature over this period was calculated by subtracting daily minimum air temperature from daily maximum air temperature.

Daily mean soil temperature at 10, 20 and 30 cm was obtained by averaging for each depth, the three readings recorded daily at 06:00, 14:00 and 22:00 hours and at 06:00 hours the proceeding day.

3.1.3. Vapour pressure deficit of the air

Vapour pressure deficit of the air, in kilopascals, was calculated using the following formula:

$$vpd = \overset{\bullet}{e}_T - e \tag{3.1}$$

where; vpd is the vapour pressure deficit of the air (kPa),

$\overset{\bullet}{e}_T$ is the saturated vapour pressure of the air (kPa), at daily mean air temperature (T), and e is the daily mean vapour pressure of the air (kPa).

Measurements of wet- and dry-bulb air temperature recorded by the energy balance system were used when available to compute vapour pressure deficit. Hourly average values of wet- and dry-bulb temperature recorded by the CR7 data logger system from 07:00 hours to 06:00 hours the following day were averaged to give twenty-four hour average values of wet- and dry-bulb air temperatures. When the energy balance system was not in operation, the average of readings of wet- and dry-bulb air temperature in the Stevenson screen, recorded at 06:00, 14:00, 22:00 hours daily and at 06:00 hours the following day were used.

Values of saturated vapour pressure of the air at the daily mean air temperature were taken from the "Smithsonian Meteorological Tables" (List, 1979), using values of daily mean air temperature calculated by the method in discussed Subsection 3.1.2. Daily mean vapour pressure of the air was recorded from the same tables, using values of $\overline{T} - \overline{T}_w$, the mean daily difference of wet- and dry-bulb temperatures, and daily mean air temperature.

3.1.4. Net Radiation

Hourly average values of net radiation (W m^{-2}) recorded by the CR7 logger data system of the energy balance system were converted MJ m^{-2} $hour^{-1}$ (see Appendix B), and added to give daily totals of net radiation (MJ m^{-2} d^{-1}). The daily totals represent the arithmetic sum of the positive and negative hourly values recorded over each 24 hour period.

Measurements of incoming solar radiation recorded by the strip-chart recorder of the pyranometer were used to estimate daily total net radiation when the energy balance system was not operational. The following equation was used to estimate daily total net radiation

$$R_n = (1-a)\ K\downarrow + L^{*} \tag{3.2}$$

where; a is albedo = 0.25 (dimensionless),

Rn is total daily net radiation (MJ m^{-2} d^{-1}),

K↓ is daily total solar radiation (MJ m^{-2} d^{-1}),

and L^{*} is the longwave radiation balance (MJ m^{-2} d^{-1}).

A value of 0.25 was selected for the albedo of the plantation site. Field "A" was bare at the beginning of the study period, since the previous year's crop had been cut to ground level during the first week of May. The *Salix* species then grew gradually throughout the study period and were morphologically most similar to an agricultural crop than any other vegetation type. Oke (1978) states that albedos of bare soil range between 0.05 (dark, wet) and 0.40 (light, dry), and that agricultural crops and natural vegetation less than one metre in height show albedos between 0.18 and 0.25. Since the ground cover was a combination of sandy soil and vegetation, a value of 0.25 was chosen as a representative average for these components.

Careful examination of the signals sent by the pyranometer to the strip-chart recorder showed that the recorder consistently overestimated peak values of solar radiation. This was confirmed by comparing theoretical maximum daily values of solar radiation, assuming an atmospheric transmissivity of 0.75, to the daily maximum values registered by the recorder. The hourly measurements of incoming solar radiation in millivolts were therefore reduced by 25% due to the suspected over-estimation by the strip-chart recorder of the signals sent by the pyranometer. The reduced millivolt readings from 06:00 to 21:00 hours daily were converted to values in MJ m^{-2} $hour^{-1}$ (see Appendix B), and added to give total daily solar radiation in MJ m^{-2} d^{-1}

The longwave radiation balance, L^*, (MJ m^{-2} d^{-1}), was modelled using Jury and Tanner's (1975) equation:

$$L^* = (0.1 + [0.9\ K\downarrow\ /\ K\downarrow_{max}])\ (\epsilon_a - \epsilon_v)\ 4.9 \cdot 10^{-9} \cdot T^4 \qquad (3.3)$$

where; (0.1 + [0.9 ...) is a cloud correction factor,

K↓ is the measured total daily solar radiation (MJ m^{-2} d^{-1}),

$K\downarrow_{max}$ is total daily solar radiation under clear sky conditions (MJ m^{-2} d^{-1}),

ϵ_a is the effective emissivity of the atmosphere (dimensionless),

$\epsilon_v = 0.96$ is the assumed emissivity of the vegetation (dimensionless),

$4.9 \cdot 10^{-9}$ is the Stefan-Boltzmann constant (MJ m^{2}·d^{-1} K^{-1}),

and T is the daily mean air temperature (K).

The daily total solar radiation under clear sky conditions, $K\downarrow_{max}$, was calculated from 0.75 $K\downarrow_0$, where $K\downarrow_0$ is the daily total solar radiation at the top of the atmosphere for 49° N (Russelo, 1974). The co-efficient of 0.75 was deemed appropriate for the site due to the relatively 'clear' atmosphere of western Newfoundland in summer. Similar values have been reported for comparative sites (Gates, 1980).

Spittlehouse (1981) tested various equations for the estimation of the effective emissivity of the atmosphere [Idso and Jackson (Aase and Idso, 1978), Swinbank, 1963, Brunt (Monteith, 1961), Brutsaert, 1975, Idso, 1980, Satterlund, 1979]. He found that Brunt's equation as modified by Monteith (1961) gave the best agreement between measured and calculated net radiation in Douglas fir forests in central Vancouver Island and attributed this to the fact that the equation was calibrated for a humid environment.

Hence, the effective emissivity of the atmosphere, ϵ_a, was calculated using Brunt's equation, as modified by Monteith in 1961:

$$\epsilon_a = 0.53 + (0.206 \cdot e_a^{0.5}) \tag{3.4}$$

where e_a is the daily mean vapour pressure of the air (kPa).

The daily mean vapour pressure of the air was calculated by the method explained in subsection 3.1.4.

Daily total net radiation calculated by equation (3.2) was tested for accuracy by analysing thirteen days within the fifty-six day study period when measured net and solar radiation data were available. The equation predicted daily total net radiation with a standard error of 1.81 MJ $m^{-2}\ d^{-1}$. The results of the regression are contained in Appendix B.

When data were not available from the energy balance system or the pyranometer, daily total net radiation was estimated from measurements of maximum and minimum air temperature from the Deer Lake climatological station. This was done for the period between May 14 and June 19, 1985 and for six days between June 20 and August 14, 1985. A multiple regression equation was created using fifty-two days of net radiation data from the energy balance system and measurements of daily maximum and minimum air temperatures from Deer Lake. The resulting equation was as follows:

$$Rn = -1.8 + 0.7\ (T_{max}) - 0.3\ (T_{min}) \tag{3.5}$$

where; Rn is daily total net radiation (MJ $m^{-2}\ d^{-1}$),

T_{max} is daily maximum air temperature (°C),

and T_{min} is daily minimum air temperature (°C).

The statistics of the regression equation (3.5) are included in Appendix B.

3.1.5. Evapotranspiration

Various methods of modelling evapotranspiration from vegetated sites have been developed and tested over the years. Approaches such as Thornthwaite (1948) imply that potential evapotranspiration is dependent mostly on air temperature and tend to show poor agreement with measured values for periods of less than one month (Spittlehouse and Black, 1984). Models such as Monteith's (1964) combination equation take into account the resistance parameters imposed by the vegetation cover. An approach of this nature is preferred as it would lead to a more accurate estimation of evapotranspiration on a daily basis; however, data on the stomatal resistance characteristics of willows were not available for this study. Federer (1979, 1982) proposed a detailed water flow model of transpiration which requires detailed analysis of the soil and root concentration at various depths and this information was also not available for this study.

Daily values of evapotranspiration in millimetres were modelled using the approach of McNaughton *et al* (1979), where the maximum daily transpiration rate is limited by the hydraulic resistance of the soil-plant system (Spittlehouse and Black, 1984). The model considers actual transpiration (E_T) from a dry canopy to be the lesser of two rates; the "energy" limited rate (E_{max}) and the "soil" limited rate ($\bar{E}_s$) (Spittlehouse and Black, 1981). Evaporation was assumed to occur on days with precipitation and to take place at the energy limited rate of transpiration.

The energy limited rate of transpiration was calculated by Priestley and Taylor's (1972) equation:

$$E_{max} = \alpha \ E_{eq} \tag{3.6}$$

where; E_{max} is the energy limited rate of transpiration (mm d^{-1}),
α is an empirical coefficient (dimensionless),
and E_{eq} is the equilibrium rate of transpiration (mm d^{-1}).

The coefficient α was assumed to be 1.26 for the purpose of this study. This value was first proposed by Priestley and Taylor (ibid) for advection free water surfaces and saturated land surfaces. Davies and Allen (1973) also found that a value of 1.26 was accurate for predicting daily evapotranspiration for well watered grass in southern Ontario, and Stewart and Rouse (1977) found similar results for a saturated sedge meadow near the coast of Hudson's Bay. McCaughey's (1978) results for a mature Balsam fir stand under potential conditions also showed an α of 1.26. Many mature forests examined have produced α values of 0.7 to 1.0 (Spittlehouse and Black, 1984). The total area of willows planted at the Pasadena nursery site comprised approximately one-third of a hectare and the fields were separated and surrounded by mature trees. The area within approximately 0.5 km of the plantation site was comprised of approximately 15 % buildings and pavement and 85 % grass and/or trees and therefore the plantation site would likely experience some differential advection according to wind direction. However, it was assumed for the purpose of this study that the nature of the fetch around the study site produced only slightly varying advective effects; thus an α value of 1.26 was selected.

The equilibrium rate of transpiration, E_{eq}, was calculated from the following equation

$$E_{eq} = (s / [(s + \gamma) L_v \rho_w]) (R_n - G) \tag{3.7}$$

where; E_{eq} is the equilibrium rate of transpiration (mm day^{-1}),

s is the slope of the saturated vapour pressure/temperature curve (kPa °C^{-1}),

γ is the psychrometric constant (kPa °C^{-1}),

L_v is the latent heat of vapourisation of water (MJ kg^{-1}),

ρ_w = 1,000, the density of water (kg m^{-3}),

R_n is the daily total net radiation (MJ m^{-2} d^{-1}),

and G is the daily total soil heat flux (MJ m^{-2} d^{-1}).

The values for slope of the saturated vapour pressure/temperature curve (s), at daily mean air temperature, were taken from the "Smithsonian Meteorological Tables" (List, 1979). The values for the latent heat of the vapourisation of water, L_v, at daily mean air temperature, were taken from Oke (1978). These daily values are displayed in Tables B-1 and B-7 in Appendix B.

The values of daily total net radiation discussed in subsection 3.1.6 and calculated from equations (3.2) and (3.5) were used for values of Rn in equation (3.7). The daily total soil heat flux, G, was estimated as a percentage of total daily net radiation. It was assumed to be 25% of total daily net radiation on June 20, 1985, as the soil then had minimal vegetation cover since the previous year's growth had been cut to ground level during the first week of May, and the present season's growth had just begun. The value of 25% might be considered a reasonable estimate of the daily total heat flux as a percentage of total daily net radiation for a bare soil (Oke, 1978). This percentage was then reduced, as shown in Table B-7 of Appendix B, throughout the 56 days of the study period to a value of 10% of total daily net radiation when the canopy was mature and closed.

Equation (3 7) gives a value for the equilibrium rate of evapotranspiration in metres per day. The resulting values were multiplied by 10^3 to obtain estimations in mm per day.

The soil water supply limited rate of transpiration was calculated by the following equation, as suggested by McNaughton et al (1979):

$$E_s = b\ \theta_e \tag{3.8}$$

where; b = 24 mm day^{-1} (see below)

and,

$$\theta_e = (\theta - \theta_{min}) / (\theta_{max} - \theta_{min}) \tag{3.9}$$

where: θ_e is the fraction of extractable water in the root zone (dimensionless),
θ is the volumetric water content of the root zone (dimensionless),
θ_{min} = 0.11, the volumetric water content at the permanent wilting point (dimensionless),
and θ_{max} = 0.30, the volumetric water content at field capacity (dimensionless).

Equation (3.8) therefore assumes that a linear relationship exists between the soil limited rate of transpiration and the fraction of extractable water in the root zone, θ_e. The root zone was considered to be the top 20 cm of the soil, as this is the extent of maximum concentration of the roots of plantation-grown willows in their third season of growth (Ericsson, 1984). The value of b = 24 mm d^{-1} was estimated from consideration of the typical moisture retention properties of the soil and the derivation of this value is contained in Section B.4. of Appendix B.

The volumetric water content of the root zone, θ, was estimated on a daily basis by performing water balance calculations using daily precipitation data and estimates of evapotranspiration during the study period. The methodology used in calculating the daily water balance is discussed in Subsection 3.1.6.

Values of the volumetric water content of the root zone at the permanent wilting point (-20 bar suction) and at field capacity (-0.1 bar) are typical values for a sandy loam soil (Spittlehouse, personal communication).

The daily water deficit was calculated as the energy limited rate of evapotranspiration (E_{max}) minus the actual rate of transpiration (E_T). This represents the inability of the vegetation to meet the daily atmospheric evaporative demand for water when the amount of available water in the soil is low (Spittlehouse and Black, 1981).

3.1.6. Water Balance Calculations

A water balance of the top 20 cm of the soil at the Pasadena nursery site was estimated for two time periods; May 14 to June 19, and June 20 to August 14, 1985. The first time period was examined in an attempt to estimate a starting value for soil water content on June 20, when meteorological variables and the growth of *Salix* were analysed on a daily basis for an eight week period.

May 13 was the date of the last recorded snowfall (2.0 cm) at the Deer Lake climatological station and snow was still present in small patches at the nursery site on this date. It was assumed that the soil moisture was at field capacity (-0.1 bar) on May 13 and therefore that the water content of the top 20 cm of the soil was 60 mm (0.30 x 200 mm). The daily energy and soil limited rates of evapotranspiration were calculated using equations (3.6) and (3.8) respectively. The values of daily total net radiation for May 14 to June 19 were estimated by equation (3.5) using measurements of maximum and minimum daily temperatures from the Deer Lake climatological station. Daily soil heat flux, G, in equation (3.7) was assumed to be 25% of daily total net radiation. Daily total precipitation in mm day^{-1} recorded at Deer Lake was used in the calculation of the water balance during this time period. The daily value of E_{max} or E_s, whichever was less, was subtracted from the daily water content of the soil on days without precipitation. On days when precipitation occurred, the energy limited rate of evapotranspiration was subtracted from the amount of precipitation recorded, and the result was added or subtracted from that day's value of the water content of the soil. It was, therefore, assumed that intercepted rainfall evaporated at the same rate as transpired water. Water content of the soil in excess of 60 mm was assumed to be lost to run-off. The values used in the calculation of the daily water balance for this time period are displayed in Section B.5 of Appendix B.

The calculation of the water balance for May 14 to June 19 indicated that the soil was likely still at field capacity on June 19, 1985. The daily water content of the soil for June 20 to August 14 was calculated as above, with the exception that the energy limited rate of evapotranspiration was calculated using either i) measured values of net radiation at the site or ii) modelled values of net radiation from on site measurements of incoming solar radiation or iii) modelled net radiation from on site measurements of maximum and minimum daily temperatures using equation (3.5). The values used in the calculation of the daily water balance for June 20 to August 14 are displayed in Section B.6. of Appendix B.

3.1.7. Wind speed

Hourly values of wind speed in miles per hour, read from the strip-charts of the Esterline-Angus recorder were converted to values in metres per second. The hourly values were converted to daily mean values by averaging the readings from 06:00 hours to 06:00 hours the proceeding day. The daily mean values of windspeed between June 20 and August 14 are contained in section B.7. of Appendix B.

3.2. Statistical Analysis

3.2.1. Growth measurements

Weekly mean height of *Salix purpurea*, *S. viminalis* and *S. alba* shoots for June 10 to October 7, 1985 were plotted against Julian day and a regression line was fitted to the data. Weekly mean base diameter of *Salix purpurea*, *S. viminalis* and *S. alba* shoots was also regressed against Julian day for the period between June 24 to October 7. An analysis of variance of the final shoot heights and base diameters of the three species as recorded on October 7, 1985 was conducted to determine if a significant difference existed between the species in overall growth.

Daily total shoot height and base diameter of each of the three species between June 20 and August 14 were also plotted against Julian day and an unplanned comparison among the regression coefficients (Sokal and Rolhf, 1982) was conducted to determine if a difference existed for the within-season pattern of growth.

3.2.2. Daily growth and climatic variables

The daily values of each of the climatic variables were separately regressed against the corresponding daily mean height and diameter increment change for each species from June 20 to August 14, 1985. A T-test of each of the regression coefficients (Neter et al, 1983) was performed to test for a significant linear relationship between the climatic variables and the daily height and base diameter increment change. Each of the previous day's climatic variables was also regressed against the daily mean height and diameter increment changes for each species and also tested for a significant linear relationship with a T-test of the resulting regression coefficients.

A stepwise multiple regression (Dixon, 1985) was performed with daily growth increment change of each of the species as the dependent variable, and the daily value of each of the climatic variables that proved to have a significant linear relationship with daily growth, as the independent variables.

Several criteria were set for the selection of the independent variables used in the multiple regression model. The F^* statistic of each independent variable was calculated at each step in the selection procedure. The F^* statistic is equal to the regression mean square divided by the error mean square of the independent variable about to be entered into the model, and is therefore a measure of the reduction in the total variance associated with the use of the variable (Neter *et al*, 1983). The minimum acceptable value of the F^* statistic was set at 4.00 which is the critical value for F at a significance level of 0.05 with 1 and 50 degrees of freedom.

The degree of correlation among the independent variables eligible for entry into a multiple regression model will affect the interpretation of the final results (Neter *et al*, 1983). If the independent variables included in the multiple regression model are intercorrelated with each other or are correlated with any other independent variables associated with the dependent variable not included in the model, the regression cannot be interpreted effectively (ibid). The magnitude of the regression coefficients will be dependent on the other variables included in the model and those which have not been included. The tolerance of a variable about to be entered into the model is the reciprocal of the variance inflation factor, or 1 minus the r-squared value of the variable (Neter *et al*, 1983). The tolerance assigned in the stepwise selection procedure in the present study was 0.80. Therefore, a variable was not entered into the model unless it's multiple correlation coefficient with the other variables already in the model was 0.20 or less. A variable was also not entered if it's entry caused the multiple correlation coefficient of any previously entered variable to exceed 0.20 (1.0 minus the tolerance value, 0.80).

The BMDP 2R program (Dixon, 1985) initially calculated an F^* statistic for each independent variable eligible for entry into the model. The independent variable with the highest F^* statistic was selected first for entry into the model. The program then fitted the regression model using two independent variables, with the first variable selected being one of the pair. F^* statistics were calculated for each independent variable not yet entered into the model and the independent variable that, when combined with the first variable entered, resulted in the highest F^* statistic was entered next into the model. This procedure continued until all independent variables that met the selection criteria discussed above were entered into the model.

Chapter 4
Results

4.1. Growth Measurements

4.1.1. Weekly height growth, June 10 to October 7, 1985

The total mean heights of *Salix purpurea*, *S.viminalis* and *S.alba* shoots recorded once weekly from June 10 to October 7, 1985 are displayed in Figure 4-1. Maximum rate of height growth for all species occurred between June 17 (Julian day 168) and July 29 (JD 210). All three species had achieved 50% of their final mean heights by July 15 (JD 196). *Salix purpurea* and *S.alba* had grown to 90% of their final mean heights by August 12 (JD 224) while *S.viminalis* did not reach 90% of its final mean height until August 26 (JD 238).

Table 4-1 displays the results of a least-squares regression of weekly total mean height of each of the species on Julian day. BMDP program 5R (Dixon, 1985) was used to test the applicability of fitting a polynomial regression model to the data. The program calculates a t-statistic for each degree of the independent variable. A significant value of t indicates that the regression coefficient at that degree is not equal to zero and therefore that the term is needed in describing the model (Neter et al, 1983). All three species showed that linear and quadratic effect coefficients were significant in modelling the response function of height growth from June 10 to October 7, 1985.

The BMDP 5R program also calculates a goodness of fit test at each degree of the polynomial regression for the orthogonal polynomial of the next highest degree. The numerator of the F statistic (F^*) is the sum of squares attributed to the orthogonal polynomial of the next highest degree and the denominator is the residual sum of squares from the fit to the next highest degree orthogonal polynomial. A significant F statistic therefore indicates that a higher degree polynomial should be considered in the model (Dixon, 1985).

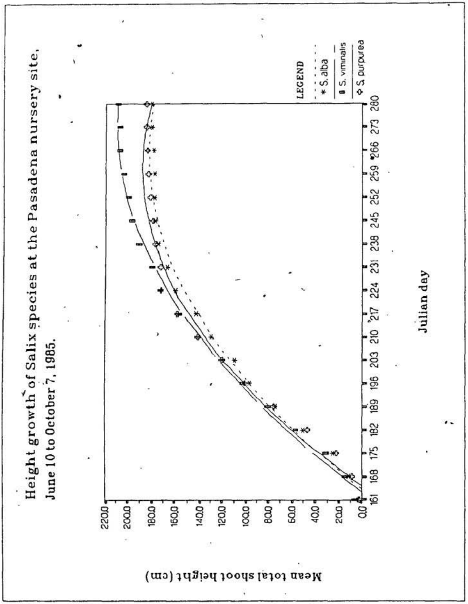

Figure 4-1: Height growth of *Salix* species at the Pasadena nursery site, June 10 to October 7, 1985.

Table 4-1: Results of least-squares polynomial regression of total mean shoot-height on Julian day, June 10 to October 7, 1985, n = 18, critical value of t(0.001; 17) = 3.965

Species	Degree of the polynomial	Regression coefficient	Standard error of the regression coefficient	t	Multiple r^2
S.purpurea	0	-1211.5	85.5	-14.17	
	1	10.7	0.79	13.59	
	2	-0.021	0.0018	-11.52	0.98
S.viminalis	0	-1070.2	56.9	-18.81	
	1	9.33	0.53	17.74	
	2	-0.02	0.0012	-14.30	0.99
S.alba	0	-1079.8	61.5	-17.55	
	1	9.52	0.57	16.75	
	2	0.02	0.0013	-13.96	0.99

Table 4-2 displays the results for the goodness of fit test for the second-order polynomial models created to explain the variation in height growth of the *Salix* species studied in 1985. The goodness of fit test for all three species indicated that a second-order model was adequate in describing the pattern of height growth of the *Salix* species examined in 1985. F-statistics calculated for the zero and first degree of the polynomials were both significant at the 0.001 level indicating that a higher order polynomial was required in the model. The F-statistic calculated for the second order polynomial for all three species was not significant at the 0.001 level and therefore suggests that a higher degree of polynomial is not required to describe the pattern of height growth in 1985.

Table 4-2: Results of goodness of fit test for least-squares polynomial regression of total mean shoot height on Julian day, June 10 to October 7, 1985, n=16.

Species	Degree of the polynomial	F*	Numerator degrees of freedom	Denominator degrees of freedom	Critical F value(0.001)
S.purpurea	0	313.6	3	14	9.7
	1	66.6	2	14	11.8
	2	1.0	1	14	17.1
S.viminalis	0	1090.0	3	14	9.7
	1	137.7	2	14	11.8
	2	5.8	1	14	17.1
S.alba	0	682.4	3	14	9.7
	1	120.2	2	14	11.8
	2	4.2	1	14	17.1

The mean total height of *S.viminalis* shoots recorded on October 7, 1985 was 208.7 cm. *S.purpurea* and *S.alba* shoots grew to final mean heights of were 183.3 and 179.6 cm respectively. The final mean heights of the species were tested for equality in an effort to detect differences in overall height attainment during the 1985 growing season. A BMDP 1V program (Dixon, 1985) for analysis of variance was used to determine whether the mean total shoot heights of each of the three species recorded on October 7, 1985 were significantly different from one another. The results of the one-way analysis of variance are displayed in Table 4-3. The F value of 10.53 for 2 and 87 degrees of freedom is significant at the 0.0001 level, indicating that the three species were significantly different in their mean final height attainment.

Table 4-3: One-way analysis of variance table of mean total shoot height recorded on October 7, 1985, by species.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Value	Significance
Between Species	14,984	2	7,492	10.53	0.0001
Within Species	61,919	87	711		
Total	76903	89			

4.1.2. Daily height growth, June 20 to August 14, 1985

The total shoot height was measured on a daily basis for eight weeks between June 20 and August 14, 1985. Daily total height of the thirty shoots of each species was regressed on Julian day from June 20 (JD 171) until August 14 (JD 226). A linear relationship between day and total shoot height was determined for all three species and the results of the regressions are displayed in Table 4-4. Figure 4-2 displays the daily mean total shoot height of each of *Salix purpurea*, *S.viminalis* and *S.alba* as a function of Julian day from JD 171 to JD 226. The measurements for the thirty shoots of each species were not displayed on the diagram due to the large number of observations in the data set.

Table 4-4: Results of least-squares regression of daily total shoot height on Julian day, June 20 to August 14, 1985, n = 1219, critical value of F(0.001; 1, 1247) = 10.8

Species	Intercept	Reg. Coef.	Standard Error of the Reg. Coef.	F Ratio	Standard Error of the Estimate	Multiple r^2
S.purpurea	-518.0	3.12	0.022	20604.9	12.6	0.94
S.viminalis	-476.2	2.93	0.016	34337.9	9.2	0.97
S.alba	-440.2	2.70	0.018	21830.1	10.6	0.95

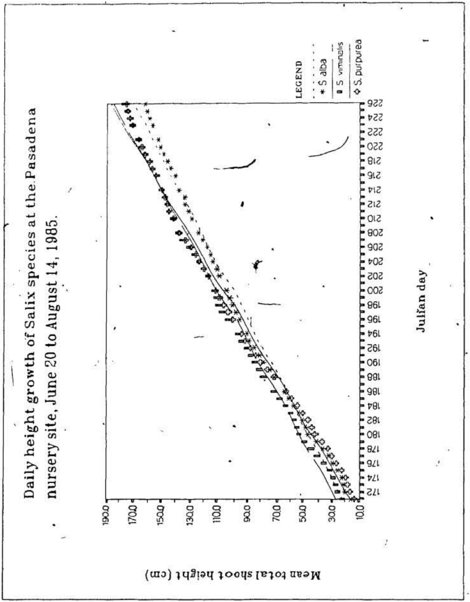

Figure 4.2: Daily height growth of *Salix* species at the Pasadena nursery site, June 20 to August 14, 1985.

The regression coefficients of the linear regression models displayed in Table 4-4 were tested for equality by an unplanned comparison of the regression coefficients (Sokal and Rohlf, 1981). The absolute difference between a pair of regression coefficients was compared to the "minimum significant difference" (MSD). The MSD was calculated as the critical value of the studentized augmented range (Q') at 2 and 1247 degrees of freedom and a significance level of 0.01, multiplied by the maximum value of the standard error of the regression coefficients being compared. If the absolute difference between the regression coefficients was greater than the calculated MSD then the regression coefficients were considered significantly different at the 0.01 level. The results of the unplanned comparisons of the linear regression coefficients of shoot height growth from June 20 until August 14 are contained in Table 4-5.

Table 4-5: Results of unplanned comparisons among the regression coefficients from the linear regression of total shoot height on Julian day, June 20 to August 14, 1985, Q'(0.01, 2, 1247) = 3.653.

Species Compared	Maximum Standard Error of the Regression Coefficients	MSD	Absolute Difference of the Regression Coefficients
S.purpurea *S.viminalis*	0.022	0.080	0.19
S.purpurea *S.alba*	0.022	0.080	0.42
S.viminalis *S.alba*	0.018	0.066	0.23

The comparison of all pairs of regression coefficients resulted in the absolute difference between them being greater than the calculated value of the minimum significant difference at the 0.01 level. Therefore it was assumed that the slopes of the linear regression models of the three species' total shoot height from June 20 and August 14, 1985 were significantly different from one another.

The mean daily height increment change of each species from June 20 (JD 171) to August 14 (JD 226) is displayed in Figure 4-3. Measurements of daily mean shoot height increment change were missing for Julian days 187, 194 and 195 The greatest values of mean daily height growth for all species occurred between days 175 (June 24) and 179 (June 29). The largest amount of growth in a 24 hour period was experienced by *Salix alba* shoots on JD 179 when mean height growth was 5.6 cm. Daily height growth increment change was least for all species on Julian day 226 when the mean height growth was less than 1.0 cm for all three species

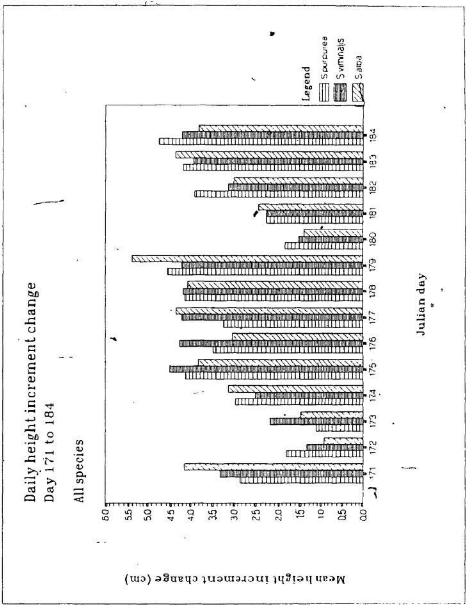

Figure 4-3: Bar graph of daily height increment change for all species, June 20 to August 14, 1985.

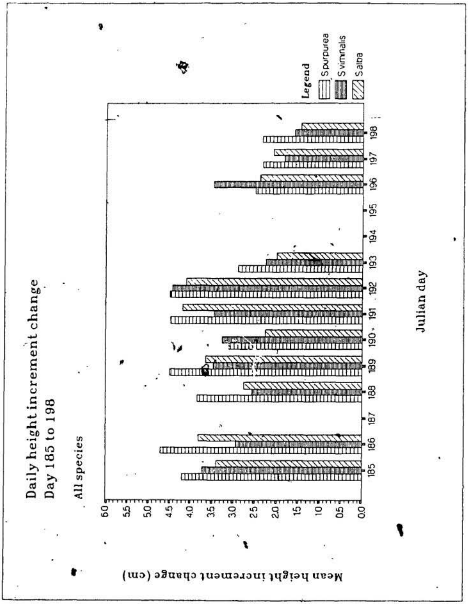

Figure 4-3 [Cont.]: Bar graph of daily height increment change for all species, June 20 to August 14, 1085.

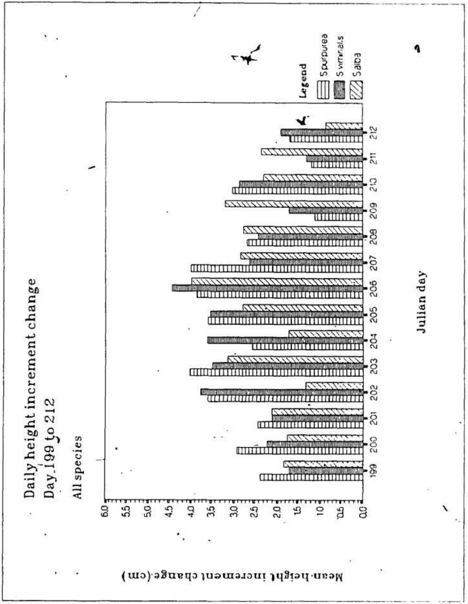

Figure 4-3 [Cont.]:Bar graph of daily height increment change for all species, June 20 to August 14, 1985.

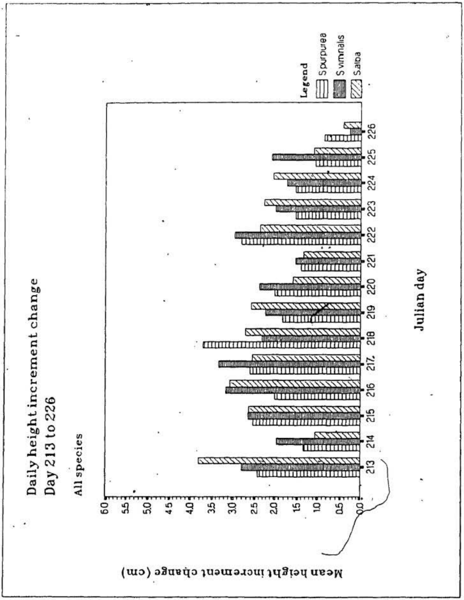

Figure 4-3 [Cont.]:Bar graph of daily height increment change for all species, June 20 to August 14, 1985.

4.1.3. Weekly base diameter growth, June 24 to October 7, 1985

Figure 4-4 displays the weekly mean shoot base diameter of *Salix purpurea*, *S.viminalis* and *S.alba* from June 24 (JD 175) to October 7 (JD 280). The base diameter was too difficult to measure prior to June 20 due to the small size of the shoots (< 0.6 cm base diameter) *S.viminalis* and *S.alba* shoots grew to a mean base diameter of 1.5 cm and 1.1 cm respectively on October 7, while *S.purpurea* attained a final mean base diameter of 1.1 cm. *S.purpurea* grew to 90% of its total mean base diameter by August 15 (JD 227). *S.alba* and *S.viminalis* attained 90% of their final mean base diameters by August 26 (JD 238) and September 2 (245) respectively.

A least-squares polynomial regression model was fitted to the weekly measurements of mean total base diameter for each of the three species using the BMDP 5R program (Dixon, 1985). The results are contained in Table 4-6. The regression of *Salix purpurea* on Julian day resulted in a third-order polynomial with the t-tests of the regression coefficients of all three degrees of the polynomial being significant at the 0.001 level. The regression *S.viminalis* and *S.alba* both resulted in a second-order polynomial model with the linear and quadratic coefficients significant at the 0.001 level.

Table 4-7 displays the results of the goodness of fit test (Dixon, 1985) at each degree of the polynomial regression for *Salix purpurea*, *S.viminalis* and *S.alba* weekly base diameter growth in 1985. The F-statistic for the third degree of the polynomial regression for *S.purpurea* was not significant at the 0.001 level indicating that a higher order is not required to model weekly base diameter growth in 1985. *S.viminalis* and *S.alba* had non-significant F-statistics at the second order of the polynomial suggesting that the quadratic term was satisfactory in modelling weekly base diameter growth from June 24 to October 7 and a higher order was not required.

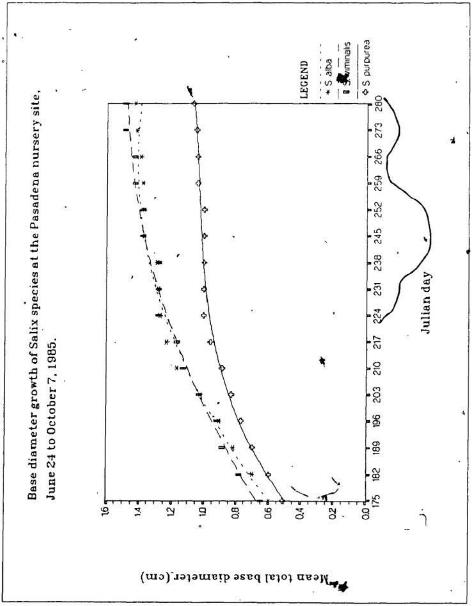

Figure 4-4: Base diameter growth of *Salix* species at the Pasadena nursery site, June 24 to October 7, 1985.

Table 4-6: Results of least-squares polynomial regression of weekly total mean shoot base diameter on Julian day, June 21 to October 7, 1985, n = 16, critical value of t(0.001; 15) = 4.073.

Species	Degree of the polynomial	Regression coefficient	Standard error of the regression coefficient	t	Multiple r^2
S.purpurea	0	-13.4	1.9	-7.09	
	1	0.17	0.025	6.56	
	2	-0.0006	0.0001	-5.74	
	3	0.0000008	0.0000002	5.10	0.99
S.viminalis	0	-3.91	0.38	-10.27	
	1	0.038	0.0034	11.13	
	2	-0.00007	0.000008	-8.89	0.99
S.alba	0	-5.60	0.46	-12.14	
	1	0.053	0.0041	12.85	
	2	-0.0001	0.000009	-11.04	0.99

Table 4-7: Results of goodness of fit test for least-squares polynomial regression of total mean shoot base diameter on Julian day, June 24 to October 7, 1985, n=16.

Species	Degree of the polynomial	F^*	Numerator degrees of freedom	Denominator degrees of freedom	Critical F value(0.001)
S.purpurea	0	500.4	4	11	10.3
	1	120.6	3	11	11.6
	2	19.5	2	11	13.8
	3	4.8	1	11	19.7
S.viminalis	0	508.9	3	12	10.8
	1	45.7	2	12	13.0
	2	2.6	1	12	18.6
S.alba	0	430.5	3	12	10.8
	1	83.1	2	12	13.0
	2	5.2	1	12	18.6

Salix purpurea shoots grew to a final mean base diameter of 1.07 cm and the mean base diameters of *S.viminalis* and *S.alba* recorded on October 7, 1985 were 1.49 and 1.44 cm respectively. The results of an analysis of variance of final mean shoot base diameter by species is displayed in Table 4-8. The calculated F value is highly significant, indicating that the final mean base diameter attainments of the three species were significantly different.

Table 4-8: One-way analysis of variance table of mean total base diameter recorded on October 7, 1985, by species.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F Value	Significance
Between Species	3.15	2	1.58	36.39	0.0000
Within Species	3.77	87	0.04		
Total	6.92	89			

4.1.4. Daily base diameter growth, June 20 to August 14, 1985

Daily total base diameter for each species of all shoots measured was regressed on Julian day from June 20 (JD 171) to August 14 (JD 226). A linear regression model was determined for all three species and the results of the least-squares regressions are contained in Table 4-9. Figure 4-5 displays daily mean total base diameter of each of *Salix purpurea*, *S.viminalis* and *S.alba* as a function of Julian day from JD 171 to JD 226. The daily means of each species are shown rather than the measurements of all ninety shoots as the number of data points (1,249) was too large to be displayed.

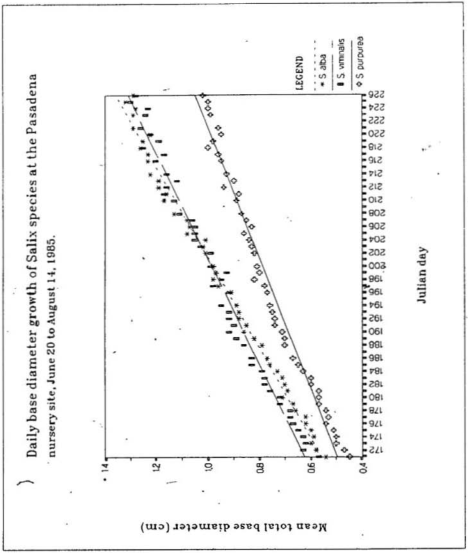

Figure 4-5: Daily base diameter growth of *Salix* species at the Pasadena nursery site, June 20 to August 14, 1985.

Table 4-9: Results of least-squares regression of daily total shoot base diameter on Julian day, June 20 to August 14, 1985, n = 1249, critical value of F(0.001; 1, 1247) = 10.8.

Species	Intercept	Reg. Coef.	Standard Error of the Reg. Coef.	F Ratio	Standard Error of the Estimate	Multiple r^2
S.purpurea	-1.22	0.0100	0.00019	2711.7	0.11	0.69
S.viminalis	-1.58	0.0128	0.00026	2492.9	0.15	0.67
S.alba	-1.93	0.0145	0.00026	3100.1	0.15	0.71

The regression coefficients from the linear regression models of each species displayed in Table 4-9 were tested for equality by an unplanned comparison of the regression coefficients as described in Subsection 4.1.1. The results of the unplanned comparisons of the linear regression coefficients of daily base diameter growth from June 20 to August 14 are contained in Table 4-10. The comparison of all pairs of regression coefficients resulted in the absolute difference between them being greater than the calculated value of the minimum significant difference at the 0.01 level. The slopes of the linear regression models of daily total base diameter were therefore considered significantly different from one another.

The mean daily base diameter increment change for the three species between June 20 (JD 171) and August 14 (JD 226) is displayed in Figure 4-6. Daily base diameter increment change data was not recorded for Julian days 187, 194 and 195. Shrinkage of the stems was recorded for several 24 hour periods from June 20 to August 14, 1985. The species varied in their amount of daily base diameter increment change, with some species showing a shrinkage and others showing an increase during the same 24 hour period (i.e. JD's 172, 176, 180, 190, 191, 197, 212 etc.). The largest recorded stem shrinkage in a 24 hour period was experienced by *Salix viminalis* shoots on Julian day 218 when the mean base diameter of all shoots was 0.06 cm less than that recorded on the previous day. Mean daily base diameter increases of 0.07 cm were experienced by *S.purpurea* shoots on Julian day 221 and *S.viminalis* shoots on Julian days 19[illegible]d 217.

Table 4-10: Results of unplanned comparisons among the regression coefficients from the linear regression of total shoot base diameter on Julian day, June 20 to August 14, 1985, Q'(0.01, 2, 1247) = 3.653.

Species Compared	Maximum Standard Error of the Regression Coefficients	MSD	Absolute Difference of the Regression Coefficients
S.purpurea *S.viminalis*	0.00026	0.00095	0.0028
S.purpurea *S.alba*	0.00026	0.00095	0.0044
S.viminalis *S.alba*	0.00026	0.00095	0.0017

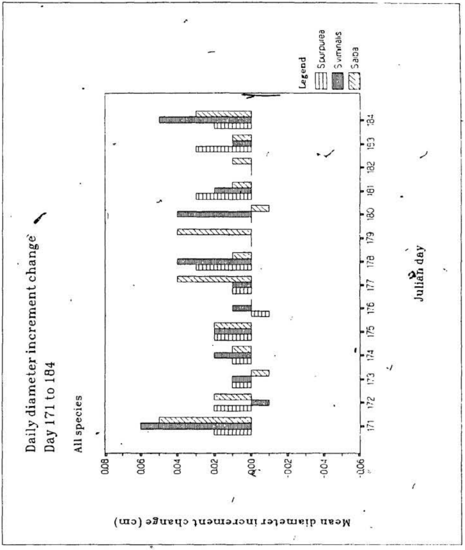

Figure 4-6: Bar graph of daily base diameter increment change for all species, June 20 to August 14, 1985.

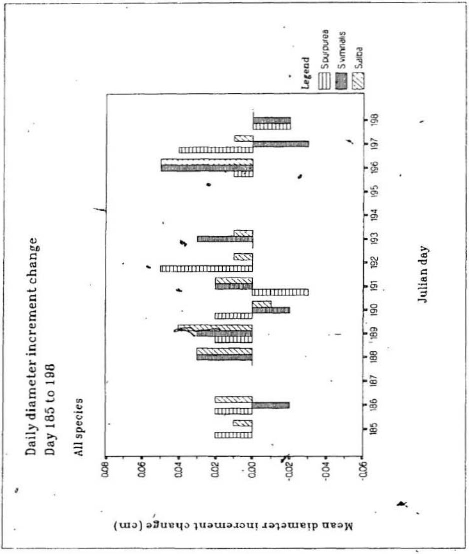

Figure 4-6 [Cont.]: Bar graph of daily base diameter increment change for all species, June 20 to August 14, 1985.

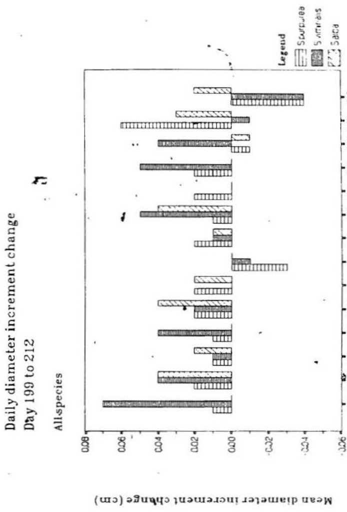

Figure 4b [Cont.]:Bar graph of daily base diameter increment change for all species, June 20 to August 11, 1985.

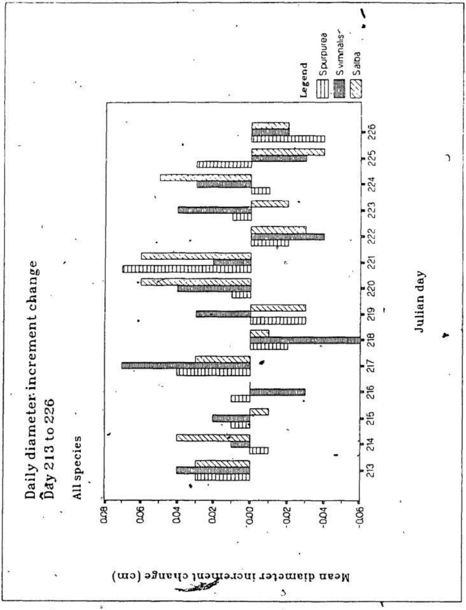

Figure 4-6 [Cont.]: Bar graph of daily base diameter increment change for all species, June 20 to August 14, 1985.

4.2. Daily growth and climatological measurements

The daily increment growth measurements of shoot height and base diameter between June 20 and August 14, 1985 were examined with respect to daily climatic variables recorded at the site in an effort to determine the effect of the local climate on daily growth. Stepwise multiple linear regression was performed on the data in an attempt to ascertain which climatic variables exerted the most influence over the daily growth of the *Salix* species examined during the 1985 growing season.

4.2.1. Testing for linear relationships between daily growth and climatological measurements

An assumption of stepwise multiple linear regression is that each of the independent variables included in the model has a significant linear relationship with the dependent variable (Neter et al, 1983). The daily mean values of height and base diameter increment change from June 20 to August 14 for each of the three species were regressed against the daily values of each of the climatic variables monitored, using the BMDP 1R program (Dixon, 1985). Daily values of mean height and base diameter increment change were also regressed against the values of the previous day's climatological variables for the same time period. Table 4-11 contains a list of the climatological variables tested for significant linear relationships with daily mean shoot height and base diameter growth.

The results of the individual least-squares linear regressions are contained in Appendix C. The presence of a significant linear relationship between each climatological variable and daily height and base diameter increment change was tested by examining the t statistic for each linear regression coefficient. The critical value of t at a significance level of 0.001 for 50 degrees of freedom was 3.50. A significant linear relationship was assumed to exist between the climatological variable and daily height or base diameter increment change if the value of the t statistic was greater than the critical value.

Table 4-11: List of daily climatological variables tested for significant linear relationships with daily height and diameter increment change.

Climatological Variables
Mean air temperature (°C)
Maximum air temperature (°C)
Minimum air temperature (°C)
Range in air temperature (°C)
Mean soil temperature at 10 cm (°C)
Mean soil temperature at 20 cm (°C)
Mean soil temperature at 30 cm (°C)
Mean vapour pressure deficit of the air (kPa)
Total net radiation (MJ m^{-2} d^{-1})
Evapotranspiration (mm d^{-1})
Mean wind speed (m sec^{-1})
Soil water content of the root zone (mm)
Water deficit (mm d^{-1})
Hours of daylight (hours)

Tables C-1, C-3 and C-5 in Appendix C contain the results of the least-squares linear regressions of the mean daily height increment change of each of *S.purpurea*, *S.viminalis* and *S.alba* shoots on each of the climatic variables measured the current day. Tables C-2, C-4 and C-6 display the results of the least-squares linear regressions of the mean daily height increment change for each of the three species on each of the climatic variables recorded the previous day. Those climatic variables that showed a significant linear relationship with daily height increment change in each of the three species are displayed in Table 4-12.

Tables C-7 through C-12 of Appendix C contain the results of the regression of daily base diameter increment of each of the three species on the daily and previous day's values of the climatic variables. None of the climatic variables showed a linear relationship with daily base diameter increment change in any of the species at a significance level of 0.001.

Table 4-12: Daily and previous day's climatic variables shown to have a significant linear relationship (*) with daily height increment change, June 20 to August 14, 1985.

Climatic variable	*S purpurea*	*S viminalis*	*S alba*
Hours of daylight	*	*	*
Daily maximum air temperature	*	*	*
Daily range in air temperature		*	
Daily mean air temperature	*		
Daily mean vapour pressure deficit	*	*	*
Daily total net radiation	*	*	*
Daily total evapotranspiration	*	*	*
Previous day's hours of daylight	*	*	
Previous day's net radiation		*	*
Previous day's evapotranspiration	*	*	*

4.2.2. Stepwise multiple regression of daily height increment change on climatic variables

The daily height increment changes of *Salix purpurea*, *S.viminalis* and *S.alba* shoots from June 20 to August 14, 1985 were regressed on the independent climatic variables that were identified as having significant linear relationships with daily height growth of each of the species in subsection 4.2.1. The BMDP 2R program (Dixon, 1985) for stepwise multiple regression was used to create a multiple regression model of independent climatic variables and their explanation of the variance in daily growth of the each of the *Salix* species.

The results of the selection of independent variables by the BMDP 2R program are contained in Tables 4-13 through 4-16. Table 4-13 contains the results for step 0 for each of *S.purpurea*, *S.viminalis* and *S.alba* daily height increment change. The tolerance of all the independent variables is equal to 1.00 since no variables had been entered into the equation at this step. The partial correlation coefficient of each variable with the dependent variable is displayed, as is the F ratio for each independent variable i.e. the F ratio that would result if that variable were entered into the model. These values are termed the "F to enter values" in Table 4-13 and are a measure of the reduction of the variance in the dependent variable associated with the use of each independent variable (Neter et al, 1983).

Table 4-13: Results of stepwise multiple regression for step 0, no independent variables entered in the model.
Critical values; F(0.05, 1,50) = 4.00, Tolerance = 0.80 .

Species	Variables Entered	Climatic Variable	Partial Correlation	F to Enter Value	Tolerance
S purpurea		mean temp.	0.50	16.57	1.00
		max. temp.	0.57	21.49	1.00
		vap. def.	0.47	14.56	1.00
		net rad.	0.48	15.21	1.00
		evapotran.	0.49	15.79	1.00
		hrs. daylight	0.56	23.11	1.00
		prev. evapo.	0.48	15.34	1.00
		prev. hours daylight	0.57	23.55	1.00
S.viminalis		max. temp.	0.58	25.95	1.00
		range temp.	0.45	12.91	1.00
		vap. def.	0.54	20.45	1.00
		net rad.	0.56	23.10	1.00
		evapotran.	0.56	23.26	1.00
		hrs. daylight	0.46	13.53	1.00
		prev.net rad.	0.55	22.15	1.00
		prev. evapo.	0.57	23.51	1.00
		prev. hours daylight	0.46	13.58	1.00
S.alba		max. temp.	0.55	21.30	1.00
		vap. def.	0.54	20.89	1.00
		net rad.	0.47	14.12	1.00
		evapotran.	0.44	12.23	1.00
		hrs. daylight	0.46	13.43	1.00
		prev.net rad.	0.46	13.16	1.00
		prev. evapo.	0.42	10.85	1.00

Step 0 of the selection procedure resulted in 'daily maximum temperature' having the highest calculated F ratio for all three species if it was to be entered first into the regression model. Table 4-14 contains the results for step 1 of the selection procedure. Maximum daily temperature had been entered into each of the regression models and the partial correlation, F to enter and tolerance values were all re-calculated for each independent variable, assuming two independent variables were now in the model, one being 'daily maximum temperature'. The regression of *Salix purpurea* daily height increment growth on 'daily maximum air temperature' and 'previous day's hours of daylight' resulted in the highest calculated F ratio. The regression of *S.viminalis* and *S.alba* daily height growth on 'daily maximum temperature' and 'hours of daylight' resulted in the highest calculated F to enter value. The tolerance level of both 'previous day's hours of daylight' and 'hours of daylight' with 'daily maximum temperature' was 0.99 meaning that the two independent variables entered in each model were virtually uncorrelated with one another.

Table 4-15 displays the results of step 2 of the stepwise multiple regression procedure for each of the three models. 'Previous day's hours of daylight' was the second independent variable to be entered into the multiple regression model with *Salix purpurea* daily height growth as the dependent variable. 'Hours of daylight' was the second independent variable to be entered into the multiple regression models with each *S.viminalis* and *S.alba* daily height growth as the dependent variables. The partial correlation, F to enter and the tolerance values were all re-calculated for models with three independent variables. The highest F to enter value for *S.purpurea* daily height growth with two independent variables already entered in the model would result from the entry of 'daily mean air temperature' as the third independent variable. However, the tolerance level of mean daily air temperature was below the minimum acceptable level of 0.80. The F to enter value of the previous day's evapotranspiration was the next highest and the tolerance of the independent variable was above the acceptable level.

Table 4-14: Results of stepwise multiple regression for step 1, one independent variable entered in the model.
Critical values; F(0.05, 1,50) = 4.00, Tolerance = 0.80.

Species	Variables Entered	Climatic Variable	Partial Correlation	F to Enter Value	Tolerance
S.purpurea	max. temp.				
		mean temp.	0 08	0 28	0.35
		vap. def.	0.10	0 49	0 47
		net rad.	0.32	5.11	0 81
		evapotran.	0 47	11.11	0 96
		hrs. daylight	0.73	57.38	0 99
		prev. evapo.	0 48	11.16	0 97
		prev. hours daylight	0.73	57 50	0 99
S.viminalis	max. temp.				
		range temp.	0.23	2.60	0.75
		vap. def.	0.20	2.07	0.47
		net rad.	0.52	17.75	0.81
		evapotran.	0.57	23.24	0.96
		hrs. daylight	0.62	30.29	0.99
		prev.net rad.	0.45	12.39	0.86
		prev. evapo.	0.58	24.96	0.97
		prev. hours daylight	0.61	29.76	0.99
S.alba	max. temp.				
		vap. def.	0.25	3 28	0 47
		net rad.	0.31	5 09	0 81
		evapotran.	0.41	10 03	0 96
		hrs. daylight	0.59	26.75	0.99
		prev.net rad.	0.33	5.91	0.86
		prev. evapo.	0.40	9.18	0.97

Table 4-15: Results of stepwise multiple regression for step 2, two independent variables entered in the model.
Critical values; F(0.05, 1,50) = 4.00, Tolerance = 0.80 .

Species	Variables Entered	Climatic Variable	Partial Correlation	F to Enter Value	Tolerance
S.purpurea	max. temp. pr. hours daylight				
		mean temp.	0.53	18.68	0.31
		vap. def.	0.05	0.10	0.46
		net rad.	0.04	0.06	0.68
		evapotran.	0.24	2.96	0.77
		hrs. daylight	0.04	0.07	0.01
		prev. evapo.	0.33	5.87	0.84
S.viminalis	max. temp. hrs. daylight				
		range temp.	-0.01	0.00	0.64
		vap. def.	0.18	1.61	0.46
		net rad.	0.38	7.93	0.68
		evapotran.	0.42	10.31	0.78
		prev.net rad.	0.35	6.49	0.78
		prev. evapo.	0.48	14.63	0.84
		prev. hours daylight	-0.02	0.02	0.01
S.alba	max. temp. hrs. daylight				
		vap. def.	0.24	2.95	0.46
		net rad.	0.10	0.47	0.68
		evapotran.	0.21	2.24	0.78
		prev.net rad.	0.19	1.77	0.78
		prev. evapo.	0.24	2.89	0.84

The second step of the multiple regression stepwise procedure for the dependent variable *S.viminalis* daily height growth resulted in the entry of the independent variable 'hours of daylight'. The re-calculated values of partial correlation, F to enter and tolerance for each of the variables not yet entered into the model are displayed in Table 4-15. 'Previous day's evapotranspiration' also resulted in the highest F to enter value when combined with the already entered independent variables of 'daily maximum air temperature' and 'hours of daylight'. 'Previous day's evapotranspiration' was also the only independent variable not yet entered in the model with a tolerance value above the minimum acceptable level.

The stepwise multiple regression procedure for *S alba* daily height growth, the second step resulted in the entry of hours of daylight. The F to enter and/or the tolerance values calculated for the independent variables not yet entered in the model were all below the assigned minimum levels for variable entry

The results for step three of the selection of independent variables for the regression of daily height increment growth of *Salix purpurea* and *S.viminalis* shoots is displayed in Table 4-16. A third independent variable was not entered in the multiple regression model for daily height growth of *S.alba* shoots because the remaining variables did not meet the selection criterion for minimum F to enter value and tolerance level.

'Previous day's evapotranspiration' was the third independent variable entered in the multiple regression models for both *S.purpurea* and *S.viminalis* daily height growth. The partial correlation, F to enter and the tolerance values were all re-calculated for models with four independent variables. The independent variables not yet entered in the models all had F to enter and/or tolerance values below the minimum acceptable levels of 4.00 and 0.80 respectively

Table 4-16: Results of stepwise multiple regression for step 3, three independent variables entered in the model.
Critical values; F(0.05, 1,50) = 4.00, Tolerance = 0.80.

Species	Variables Entered	Climatic Variable	Partial Correlation	F to Enter Value	Tolerance
S.purpurea	max. temp. pr. hours daylight prev. evapo				
		mean temp.	0.51	16.64	0.30
		vap. def.	-0.02	0.02	0.44
		net rad.	-0.06	0.18	0.63
		evapotran.	0.11	0.54	0.61
		hrs. daylight	0.02	0.03	0.01
S.viminalis	max. temp. hrs. daylight prev. evapo.				
		range temp.	0.06	0.17	0.63
		vap. def.	0.10	0.50	0.44
		net rad.	0.29	4.25	0.63
		evapotran.	0.26	3.29	0.62
		prev.net rad.	0.05	0.11	0.46
		prev. hours daylight	-0.01	0.01	0.01

The stepwise procedure of the selection of independent variables for the multiple regression models of daily height increment change in the three species examined during the 1985 growing season resulted in the selection of three independent climatic variables to explain the variation in daily height growth of *Salix purpurea* and *S.viminalis* and two for *S.alba*. The relevant statistics associated with each of the multiple regression models are displayed in Table 4-17. The tolerance value for all of the variables in each of the three models was 0.84 or greater, meaning that the correlation between the independent variables in each model was not more than 0.16.

Table 4-17: Results of multiple regression of daily height increment change on daily climatic variables, June 20 to August 14, 1985, $F(0.05;1,\ 50) = 4.00$.

Dependent Variable	Intercept	Indep. Variable	Reg. Coef.	Std. Error of the Reg.Coef.	F Ratio	Tolerance	Multiple r^2
S.purpurea height increment change	-19.59	maximum temp.	0.17	0.02	54.23	0.95	0.33
		pre hours daylight	1.14	0.18	42.11	0.86	0.69
		previous evapotrn.	0.17	0.07	5.87	0.84	0.72
S.viminalis height increment change	-12.38	maximum temp.	0.15	0.02	41.51	0.95	0.34
		hours of daylight	0.70	0.16	19.45	0.86	0.59
		previous evapotrn.	0.26	0.07	14.63	0.84	0.69
S.alba height increment change	-17.30	maximum temp.	0.17	0.03	36.15	0.99	0.30
		hours of daylight	1.01	0.20	26.75	0.99	0.55

Chapter 5

Discussion and Conclusions

This chapter provides a discussion of the results of the statistical analysis of the data collected on willow growth and the potential effect of climate variables recorded during the 1985 growing season. The results are discussed with respect to the findings of related studies that examine the influence of climate on growth in other plant species.

5.1. Seasonal growth during 1985

Weekly measurements of height and base diameter growth of the three *Salix* species studied during the 1985 growing season at Pasadena were fitted to polynomial regression curves in an effort to provide a mathematical description of the pattern of growth over time. A large amount of the variation in weekly height growth of shoots for all three species (multiple $r^2 \geq 98\%$) from June 20 to October 7 was accounted for by second degree polynomial equations. The quadratic equations derived indicate that seasonal height growth progressed in a uniform curvilinear fashion. The degree of curvature of the weekly height growth curves is defined by the regression coefficient of the quadratic or squared term in the polynomial regression equations (Hunt, 1982). This term describes the rate of change in the regression coefficient of the linear term in the equation. The rate of change during the 1985 growing season of the linear terms for each of the three species was equal (-0.02). The weekly growth in shoot height of each of the three species followed an overall similar pattern, with a majority of the growth occurring between the end of June and mid to late August.

The weekly growth in base diameter of *Salix viminalis* and *S.alba* was described by second order polynomial regression models which accounted for 99 % of the variation in growth for both species. The degree of curvature described by the quadratic terms was low in comparison to the magnitude of the linear terms, suggesting the rate of change in the regression coefficient of the linear terms slowly and gradually declined during the 1985 growing season. The third order polynomial (cubic) equation derived to describe the seasonal progression of weekly base diameter growth of *S purpurea* shoots indicates a gradually diminishing decline in the rate of diameter increase between June 20 and October 7. The cubic equation accounted for 99 % of the variation in weekly base diameter growth of *S.purpurea* shoots during the 1985 growing season. The majority of the base diameter growth in *S.purpurea* shoots occurred between mid-June and mid-August. *S.alba* and *S.viminalis* shoot base diameter growth was mostly completed by the end of August.

Similar patterns of seasonal growth have been reported for some forest species of trees. Hilley and Cunliffe (1923) examined the height growth of Larch, Sitka spruce and Corsican pine for three consecutive growing seasons in Britain during the early 1920's. Height growth was defined as initiated when an increase of 1 mm or greater was measured in a 24 hour period. All three species commenced height growth between the end of April and the beginning of June, depending on the species and year of measurement. Sitka spruce and Corsican pine trees had typically completed 80% of their total seasonal height growth by the middle to end of July, and Larch trees typically completed 80% of their seasonal growth by mid-August. Worrall (1973) studied the within season growth of Norway Spruce in Ontario and found height growth began near June 10 and began to slow by mid-July. The mean date for the initiation of radial growth was May 28 and the mean date of cessation was August 13, although cessation date was highly variable. Birch *Betula pubescens* growing at 579 m in the Pennines, Britain, initiated height growth in early June and experienced nearly 90 days of linear growth before slowing at the end of August (Millar, 1965).

A similar pattern of growth has been shown in agricultural crops grown in temperate climates. Wallis *et al*, (1983) examined the accumulated weight of hay in tonnes per hectare within consecutive growing seasons in the Peace River region of Alberta and seasonal growth showed a curvilinear trend similar to that of this study. Growth of the hay commenced at the end of May and began to slow by mid-July.

Salix viminalis clone 082 grown at the Studsvik and Kopping research stations in Sweden during 1981 also showed similar seasonal growth patterns to the weekly height and diameter growth of willow species examined at Pasadena in 1985 (Eckersten *et al*, 1983; Nilsson and Eckersten, 1983; Perttu and Lindroth, 1986). The within season accumulated biomass of stems in tonnes of dry matter per hectare was derived from non-destructive measurements of shoot height and base diameter. Growth of willows in Sweden during 1981 commenced in mid-May and continued in a gentle curvilinear pattern until early September, when the rate of growth slowed to almost zero (Nilsson and Eckersten, 1983). This general pattern was also seen in the weekly height and diameter growth of *Salix viminalis* and *S.alba* clones and the height growth of *S.purpurea* clones at Pasadena in 1985, although slowing of growth occurred sooner (mid-August). *S.purpurea* shoots showed a slightly different pattern of base diameter growth than *S.viminalis* and *S.alba* shoots in that the weekly increase in base diameter between June 24 and October 7 was described by a third order polynomial equation. Base diameter increment growth of *S.purpurea* began to slow at an earlier date than did the other two species (mid-August).

The three species were significantly different from one another in their mean shoot height and base diameter attainment recorded at the end of the growing season on October 7, 1985. The final mean height of *S.viminalis* shoots was more than 20 cm greater than that of the other two species examined. *S.alba* and *S.purpurea* shoots were similar in their final mean height attainment as were *S.alba* and *S.viminalis* in their final base diameter attainment. The final mean base diameter of *S.purpurea* shoots was more than 0.36 cm less than that of the other two species and this appears to be partly due to the fact that growth slowed earlier in the season.

5.2. Daily growth, June 20 to August 14, 1985

Daily shoot height growth between June 20 and August 14 of all three of the *Salix* species examined during the 1985 growing season had a linear relationship when regressed against Julian day. *S.purpurea* shoots were found to have the fastest rate of daily height growth at just over 3 cm per day. The rates of *S.viminalis* and *S.alba* daily shoot height increase were 2.9 and 2.7 cm respectively. The rates of daily height growth of the three species were shown to be significantly different from one another by an unplanned comparison of the three regression coefficients.

Values of daily height growth have been reported in other tree species. White (1974) measured the heights of four and five year old Scots pine (*Pinus sylvestris* L.), birch (*Betula pubescens*, Ehrh.) and rowan (*Sorbus aucuparia* L.) every one to ten days on the Pennines of

England and the measurements were converted to mean values of height increment per day. Daily height growth for all three species ranged between 0 and 0.8 cm per day. Millar (1965) also measured height increment growth of *Betula pubescens* on the Pennines every two to eleven days during the 1958 growing season. The mean daily growth rate for various periods between early June and late September ranged between 0.01 and 0.50 cm. The daily growth rates of these studies were much lower than those reported above for the three *Salix* species examined in the present study. This would be expected since the species examined in Millar's (1965) and White's (1974) studies were growing under 'natural' conditions, not undergoing the cultivation practices and fertilizer treatments that were conducted at the Pasadena nursery during the 1985 growing season and in previous years. The clones used in this study were also specifically bred and tested for high rates of growth in temperate climates, and therefore faster than typical growth rates would be expected. Worrall (1973) reported similar increments of daily height growth of Norway spruce trees in Ontario to those reported for *Salix* species in the present study. Daily height growth of four Norway spruce during June and July, 1967 ranged between 0 and 3 cm per day.

The daily base diameter growth of the three species between June 20 and August 14 appeared more variable than height growth although linear regression equations were effective in describing the overall pattern of daily growth. The linear regression equations derived explained 71, 69, and 67 % of the variation in daily base diameter growth of *S.purpurea*, *S.viminalis*, and *S.alba* respectively. *S.purpurea* shoots had the slowest rate of daily base diameter increase at 0.10 mm per day. *S.viminalis* shoots had a slightly higher rate of growth of 0.13 mm per day and *S.alba* shoots were shown to have the highest rate of growth at 0.15 mm per day. The shoot base diameter was measured with hand held calipers to the nearest 0.1 mm so the potential for inaccuracy, considering the relatively small increments of daily growth, was high. A measurable decrease in base diameter was noted in all three species on certain days within the eight week period of daily measurements and it is likely that a more accurate measurement of shoot base diameter was required if meaningful interpretation of the results was to be expected. The diameter growth in trees is typically measured by dendrometer bands which are affixed to the tree and provide continual recordings of changes in the overall diameter (Kozlowski, 1968).

5.3. Daily growth and climatological measurements

Daily height increment changes between June 20 and August 14 in each of the three willow species examined were tested for significant linear relationships with twenty-eight climatic variables, fourteen from the current day and the same fourteen variables recorded the previous day. The daily height increment change in all three species showed a significant linear relationship with the current day's 'hours of daylight', 'maximum daily temperature', 'daily mean vapour pressure deficit', 'daily total net radiation', 'daily total evapotranspiration', and the previous day's 'daily total evapotranspiration'. Daily height growth of *Salix purpurea* and *S.viminalis* shoots also showed a significant linear relationship with the previous day's 'hours of daylight' and *S.viminalis* and *S.alba* shoot height growth showed a significant linear relationship with the previous day's 'daily total net radiation'. The current day's 'daily mean air temperature' and the previous day's 'daily range in air temperature' showed significant linear relationships with height growth of *S.purpurea* and *S.viminalis* shoots respectively.

The daily base diameter increment change in all three species had no significant relationships with any of the climatic variables measured in this study. This is attributed to the reasons discussed in the previous section.

5.3.1. Climatic variables with non-significant linear relationships to daily height growth

Several climatic variables were shown to be not related to the variation in daily height growth of willow species examined in this study. None of the current day's or previous day's values of minimum air temperature, mean soil temperature at 20 or 30 cm, mean wind speed, soil water content of the root zone or water deficit were shown to have a significant linear relationship with daily height growth of the three species studied.

Hilley and Cunliffe (1923) found a slight positive correlation existed between daily minimum air temperature and daily height growth of Sitka spruce, Corsican pine and Larch. This might indicate that extreme lows of air temperature result in lower amounts of daily growth in these species. Lanner (1964) argued that climatic variables such as minimum air temperature are difficult to assess in terms of their affect on tree growth since the measurement gives no indication of the duration of these temperatures. Growth would likely be affected differently by low temperatures that persist for several hours rather than a low temperature experienced briefly before sunrise. The minimum air temperatures experienced at Pasadena in 1985 were either not extreme enough to be a significant determinant of height growth or the measurement itself was not effective in assessing the impact of low air temperatures on growth.

All measurements of mean daily soil temperature also showed no significant effect on the variation in daily height growth of the three willow species studied. Kramer and Kozlowski (1960) determined that maximum growth rates of roots are dependent on the temperature of the soil when moisture is readily available in the soil. Soil temperatures therefore may have had an effect on root biomass accumulation of the *Salix* species studied but since this growth variable was not monitored, it is impossible to assess. The temperature of the soil has the potential to affect the rate at which water and minerals move into the roots and through the plant but this effect is typically only realised with very low soil temperatures (Monteith, 1981).

Daily mean wind speed also had no detectable effect on the variation in daily height growth of willows during 1985. Increased wind speeds are often assumed to result in increased rates of transpiration in plants, although Grace (1981) states that this may be an unreasonable assumption. Pitcairn and Grace (1984) studied the effect of wind on the growth of an agriculturally cultivated grass (*Festuca arundinacea*) and found that wind speeds between 1.0 and 7.0 m sec^{-1} reduced the rate of growth. The authors concluded that the wind caused abrasions on the leaf surface which increased the stomatal and/or cuticular conductances. These increased conductances resulted in an increase in the rate of transpiration and the subsequent decrease in the plant water potential, leading to a reduction of the rate of growth. The highest value of daily mean wind speed recorded between June 20 and August 14 at Pasadena was 1.8 m sec^{-1} on July 13 and typical values were less than 1.0 m sec^{-1}. These comparatively low wind speeds were unlikely to have caused any surficial abrasions to the leaves of the *Salix* species that might lead to the reduction of growth. The nursery site at Pasadena was sheltered from high wind speeds both on a micro scale, by the mature trees surrounding the fields, as well as on a local scale, by the foothills of the Long Range Mountains. Thompson (1984) examined the influence of artificial shelter on the growth of Sitka spruce and Lodgepole pine seedlings for five years following planting and concluded that the effect of reduced wind speed was significant in increasing dry weight accumulation, but only after five years of growth. He recognised that the netting used to shelter the plants from high winds was potentially modifying the surrounding air temperature and the amount of solar radiation intercepted by the plants.

Persistent, strong winds occurring in arid environments tend to have a dramatic effect on plant growth, as the resulting desiccation can lead to severe damage of plant components (Jones, 1983). The comparatively humid environment of the Pasadena nursery site meant that this potential effect was unlikely to be realised. Wind also has the potential to reduce extremes of air temperature and high humidity due to the effect of advection, where heat and water vapour are transferred from areas of relative excess to those of relative deficiency (Slayter and McIlroy, 1967). This particular effect of wind could not be examined in the present study, although the nursery site was unlikely to be free from the effects of advection. This will have influenced the estimation of the energy limited rate of evapotranspiration by the Priestley-Taylor equation (1972) which assumed an advection-free surface and an alpha coefficient of 1.26. However, since most of the area surrounding the plantation site was vegetated (approximately 85 %) it might be assumed that these effects would be minimal.

The daily soil water content of the root zone and the daily water deficit did not show significant linear relationships with the daily height incremental growth of the *Salix* species studied during 1985. This might not be expected since some literature supports measurable growth differences under conditions of different soil water potentials. Smith and Gatherum (1974), for example, tested the effect of five different soil water potentials on various plant processes of aspen-poplar hybrid clones under controlled conditions. The authors found that increasing water potentials between -15 bar and -1/3 bar resulted in increases in net photosynthesis, leaf turgidity, leaf area, stem height and fresh and dry weight. Soil water potentials above -1/3 bar resulted in a decrease in all of the above variables and this was attributed to oxygen deficiency and/or carbon-dioxide toxicity due to the decreased aeration of the soil at high water potentials. Although a dependent relationship might be expected between shoot height growth and soil water content in the present experiment due to the anticipated increase in net photosynthesis with increasing soil water content, it is possible that the leaves may have experienced an increase in area and/or weight. It may also be assumed that the soil water potentials experienced between June 20 and August 14 displayed in Table B-7 were adequate enough to support a steady rate of growth and that the day to day differences were not extreme enough to show a restriction in growth under conditions of lower soil water contents.

The daily water deficits calculated between June 20 and August 14, 1985, which represent the difference between the energy and soil limited rates of evapotranspiration, can also be used to support the claim that soil water was generally at adequate levels during this period. There were only five days of the fifty-six day study period that water deficits may have existed if daily evapotranspiration was restricted by the amount of water in the soil and took place at the soil limited rate rather than at the energy limited rate. The small number of days that this was hypothesised to occur means that it would be unlikely that a significant linear relationship would exist between daily growth and daily water deficits. The five days of potential water deficits all occurred between August 5 and 11, and a significant restriction in growth may have been noted if they had occurred more regularly throughout the study period.

The effect of water deficits on plant growth has been well documented in the literature (Kozlowski, 1968; Kramer, 1983; Raper and Kramer, 1983). Water deficit conditions exist in situations where the water potential and turgor of a plant are reduced to the extent that it restricts the normal functioning of the plant (Kramer, 1983). The initial response of plants to water stress is a reduction in the rate of cell division and expansion (Monteith, 1981). Secondary responses may include wilting, the partial or complete closure of stomata and reduction in growth (Kramer, 1983). Giles *et al* (1985) estimated growing season soil water deficits by summing water deficit values calculated by the same method used in this study, over entire growing seasons. Yearly base increment of Douglas-fir stands were found to be correlated with calculated growing season soil water deficits. Zahner and Stage (1966) calculated daily moisture stress as the difference between Thornthwaite's potential evapotranspiration and calculated soil moisture depletion and found that it accounted for 72 % of the variation in annual shoot growth of 30- to 40-year old red pine.

5.3.2. Step-wise multiple regression of daily height growth on daily climatic variables

Those climatic variables that showed significant linear relationships with daily height increment growth of the three *Salix* species between June 20 and August 14, 1985 are listed at the beginning of this section. The selection of variables by the stepwise multiple regression procedure will be discussed in the following subsection. The three species were treated separately because the unplanned comparison of the regression coefficients of daily shoot height on Julian day indicated that the rate of growth was significantly different for each of the three species. The analysis of variance of the final shoot height and base diameter also suggested that the three species were significantly different in their final height and base diameter attainment.

5.3.2.1. Current day's maximum daily temperature

The current day's maximum daily temperature was the first climatic variable to be selected in the stepwise procedure for all three *Salix* species, indicating that it accounted for most of the variance in daily height growth. This was demonstrated by the high F-to-enter values calculated by the stepwise multiple regression program for daily maximum temperature. The partial correlation coefficient of daily maximum temperature and daily height growth in each of the three species was also the highest value calculated of all the climatic variables eligible for entry into the multiple regression model. Maximum daily temperature was the only measurement of air temperature which had a significant linear relationship with the daily height growth of *S.alba* clones. Mean daily temperature and daily range in air temperature of the current day also showed significant linear relationships with daily height growth of *S.purpurea* and *S.viminalis* shoots respectively.

Millar (1965) also found that maximum daily temperature was the most significant measurement of air temperature in determining the daily growth rate of six year old birch shoots on the Pennines of England. The daily height growth of Norway spruce was found to be dependent on daily mean air temperature ($r^2 = 0.49$), although the effect of maximum temperatures was not tested (Worrall, 1973). Temperature is considered to be one of the main environmental factors that directs the expansion and extension of plant organs (Monteith, 1981). The rates of metabolic processes within a plant are typically dependent on temperature, although the degree of sensitivity may be extremely variable and the complexity of the interaction of the effect of temperature with that of other environmental variables difficult to ascertain (ibid). The rates of elongation of leaves in cereal plants have be shown to possess well defined base temperatures, (i.e. the minimum temperature required for growth to occur), as well as optimum temperatures, where elongation occurs at a maximum rate (ibid). Monteith (1981) also states that temperature is likely to be most influential when other environmental factors are not constraining.

The models tested by the Swedish Energy Forestry Project for the influence of climate on the growth of willow plantations (Nilsson and Eckersten, 1983; Eckersten *et al*, 1983; Eckersten, 1985), include a temperature dependent coefficient. This coefficient is based on daily mean air temperatures and is set a zero for daily temperatures less than or equal to 5 °C. It is also assumed that mean daily air temperatures above 15 °C do not alter the rate of growth and the coefficient for these temperatures is set equal to one. For mean daily air temperatures between 5 and 15 °C, a linear relationship is assumed and values of the coefficient would therefore range between zero and one. The overall model, which includes an estimated rate of photosynthesis and a water-growth factor, effectively simulated seasonal above-ground biomass accumulation of a willow plantation. Monteith (1981) re-iterates this relationship by stating that for agricultural crops, increasing temperature up to the optimum will tend to result in an increase in yield through the maintenance of a more rapid, or maximum rate of photosynthesis. The present study has shown, however, that for *Salix alba* and *S.viminalis* daily shoot height growth during 1985, a significant linear relationship did not exist with daily mean air temperature. In addition, daily maximum air temperature accounted for a greater amount of the variability in height growth of *S.purpurea* shoots than did daily mean air temperature.

It is interesting to note that 75% of the days within the period of daily height growth measurement experience a daily mean air temperature above 15 °C. This would support the Swedish Energy Forestry Project's assumption that mean air temperatures above 15 °C contribute no further change to the rate of growth of willows. However, in this study there did exist a relatively strong relationship between maximum daily temperature and shoot height growth in all three species. Incoming solar radiation exerts a strong control over near-surface maximum air temperatures experienced at mid and high latitudes during the summer months and it would therefore be expected that high daily maximum air temperatures at the Pasadena nursery site occurred on days where relatively clear sky conditions prevailed. It is probable that the increased amount of height growth experienced by all three *Salix* species on days with high maximum air temperatures were partly a result of the increased amounts of light available for photosynthesis under conditions of clear skies, rather than solely a reaction to increased maximum air temperatures.

5.3.2.2. Hours of daylight

The current day's hours of daylight was the second variable selected by the stepwise procedure to explain the variation in daily height growth of *Salix viminalis* and *S.alba* clones. The previous day's hours of daylight was the second variable selected to explain the variance in daily height growth of *S.purpurea* shoots. The F-value calculated for the previous day's hours of daylight in the regression model of *S.purpurea* height growth was only slightly higher (0.12) than the F-value calculated for the current day's hours of daylight. Thus, it is assumed that there was no significant time lag in the effect of this variable since the day to day change in the number of hours of daylight was quite small, and the difference in the F-values was slight.

The decreasing number of daylight hours or photoperiod may serve as a preliminary indicator that the plant should be preparing for the onset of dormancy. Millar (1965) found that during the late part of the growing season (September), the daily height growth rate in birch was strongly dependent on photoperiod. This period of shortened daylight hours was also accompanied by decreasing air and soil temperatures, and the author found that it was impossible to distinguish between the photoperiodic induction of dormancy and the slowing of growth due to low temperatures.

The selection of the variable of hours of daylight indicates the importance of photoperiod in the control of daily height growth in *Salix* species in 1985. The fact that it was essentially uncorrelated with maximum daily temperature (tolerance = 0.99) over the study period might indicate that the effect is separate from a combined effect of these two variables that could be considered a measure of the length of the growing season. During the period June 20 to August 14, 1985, the highest daily maximum temperatures did not coincide with the period of longest daylight hours. In addition, late July and early August would appear to be a premature time period for the preparation for the onset of dormancy.

The maximum number of daylight hours occurred at the period centered on the summer solstice (June 21) and gradually decreased until August 14, when the daily measurements of growth concluded. The increased number of daylight hours may provide a greater length of time for photosynthesis to occur, resulting in the greater accumulation of assimilates during longer days. Stanhill (1960) also speculated that the short, cool nights that typically accompany long days in the northern hemisphere might aid in the reduction of assimilate losses due to night time respiration.

Eckersten's (1985) model for willow growth estimates daily potential photosynthesis incorporating measures of specific leaf weight, measurements of light above and below the canopy, a light extinction coefficient and assigned values of maximum photosynthetic rate and photosynthetic efficiency. This value is integrated as a function of times of sunrise and sunset, indicating the potential effect of day length on the overall daily amount of potential photosynthesis. The site in Sweden where the model was tested was located at latitude 58° 48' N and around the summer solstice would typically experience days that were approximately two hours longer than those experienced at the Pasadena site in the present study. The number of hours of daylight would decrease more rapidly in late summer, however, at the more northern site in Sweden. Regardless of the greater range in day length experienced in Sweden, it does seem possible that the effect of longer day length on growth at the experimental plantation in Newfoundland was realised through it's effect on daily photosynthesis.

5.3.2.3. Previous day's evapotranspiration

The final climatic variable selected for the multiple regression model derived to account for the daily variation in shoot height growth of *S.purpurea* and *S viminalis* shoots was the calculated value of total evapotranspiration of the previous day. None of the climatic variables not yet selected in the regression model explaining the daily height growth variation in *S alba* clones met the assigned level of the minimum acceptable F-to enter value. The fact that the previous day's total evapotranspiration was entered into both regression models before the current day's value of the same variable suggests that a slight time lag may exist between the action of evapotranspiration and the effect that it has on measurable shoot growth.

The positive relationship between growth and transpiration has been demonstrated in various other plant species, and it is generally acknowledged that a positive relationship exists between accumulated dry matter production and accumulated transpiration (Wallis *et al*, 1983). Rose *et al* (1972), found growth of a cultivated legume (Townsville stylo) in Australia to be well correlated with modeled values of transpiration. This relationship between transpiration and growth formed the basis of Wallis *et al*'s (1983) model of hay crop growth in the Peace River region of Alberta. The growth of above ground dry matter of hay during four growing seasons was effectively modeled from estimates of transpiration and the ratio of growth to transpiration for hay. Wallis *et al* (1983) advocate the importance of this relationship in the modelling of growth since the estimate of transpiration incorporates the effect of the limitations imposed by both the supply of energy and the supply of water.

Stanhill (1960) demonstrated that for well watered grass in seven different locations between Trinidad and Denmark, a linear relationship existed between potential evapotranspiration and growth. This relationship gives rise to the term 'water use efficiency' which is the ratio of dry matter produced to the amount of water used in transpiration (Blake *et al*, 1984). Stanhill (1960) found water use efficiency was highest at higher latitudes; and attributed this to the effect of short cool nights which limit losses of assimilates via respiration as discussed in paragraph 5.3.2.2. Blake *et al* 1984 studied the water use efficiency of seventeen poplar clones and hybrids used in short rotation forestry and found that those clones which had increased resistance to water loss produced the greatest amount of dry matter in relation to amount of water used. This was well correlated with high stomatal resistance characteristics found in the most water efficient clones and the subsequent restriction in water loss via transpiration.

The values of daily evapotranspiration used in the present study were calculated by the method used by Wallis *et al* (1983) where evapotranspiration was calculated as the lesser of energy limited and soil limited rates. Spittlehouse and Black (1981) calculated the water balance of two Douglas fir stands in British Columbia using the single layered root zone model employed in this study and found good agreement between measured and modelled soil water content on a daily basis. The success of modeling soil water content in Spittlehouse and Black's experiment indicates the effectiveness of the estimation of daily evapotranspiration which is used in the model. Since soil water content was not measured in the present study, it is impossible to ascertain the accuracy of the daily evapotranspiration estimates. Ideally, the coefficients used in the model should be established empirically through the detailed measurement of the water balance (Spittlehouse and Black, 1981).

Regardless of these limitations, it appears that the calculated values of daily evapotranspiration used in this study might be considered reasonable estimates since they did have a significant relationship with daily height growth. It is difficult to assess the relative importance of this variable as compared to those not selected by the step-wise procedure since the F-to enter values were calculated with respect to the variables already entered into the model. The positive relationship between the previous day's evapotranspiration and daily height growth suggests that there was adequate available water in the soil to support maximum rates of transpiration between June 20 and August 14, 1985. This is confirmed by the low number of days that were thought to have potential water deficit conditions, where the rate of evapotranspiration was limited by the low amount of water in the soil. A negative relationship would likely have existed between calculated daily evapotranspiration and daily shoot height growth had water been limiting as the demand for water from the atmosphere would lower the internal water potential of the plant and stress conditions might result. The closure of the stomata is an initial response to stress conditions, limiting the inward flow of carbon-dioxide from the atmosphere and lowering the rate of photosynthesis.

Eckersten's (1985) model for willow growth in Sweden includes a complex "water-growth-factor" which simulates the flow of water through the plant. It incorporates the degree of potential water stress conditions as (i) a function of the ratio of daily actual transpiration to daily potential transpiration and (ii) a parameter which estimates the relationship between this ratio and the ratio of actual to potential photosynthesis under non-water limited conditions. Actual growth is equal to the rate of potential photosynthesis multiplied by the temperature function discussed in paragraph 5.3.2.1 and the water-growth-factor. The water-growth-factor is equal to one when transpiration is occurring at a maximum rate and is not subject to limitations due to low amounts of available water. This in turn would mean that it was not restricting the rate of photosynthesis due to the increased stomatal and mesophyll resistance created by limited available water. The model showed good agreement with actual measured growth of plantation grown willows in Sweden, and Eckersten (1985) concluded that the essential processes had therefore been included in the model. The present study appears to support the importance of water availability in promoting maximum rates of growth, since the previous day's evapotranspiration accounted for part of the variance in daily height growth for two of the species examined.

5.3.3. Differences between the species

The daily height growth of each of the species was regressed separately against the climatic variables for the reasons discussed in subsection 5.3.2. The step-wise multiple regression procedure resulted in the selection of three climatic variables which accounted for 72 % and 69 % of the variance in daily height growth of *S.purpurea* and *S.viminalis* shoots respectively. Two climatic variables were selected to account for 55 % of the variance in the daily height growth of *S.alba* shoots.

The low correlation among the independent variables (≤ 0.16) entered in the model means that it is possible to speculate on the relative importance of the climatic variables. It must be remembered, however, that these variables were correlated with independent variables related to the dependent variable of daily height growth and not entered into the model. This means that the regression coefficients should not be considered in terms of the inherent effect of the independent variable on daily height growth, but rather as a partial effect (Neter *et al*, 1983). In addition, the independent variables were selected for entry into the multiple regression model with respect to the variables already entered into the equation. For example, the second independent variable entered into the multiple regression models created in this study were those which explained most of the variance in daily height growth when combined with the already entered variable of daily maximum air temperature. Variable selection was therefore dependent on the first independent variable entered.

Daily maximum air temperature of the current day was the first climatic variable selected to explain the variation in daily height growth for all three species. The three regression coefficients for maximum air temperature were nearly equal (see Table 4-17) indicating that the three species responded in a similar way to high air temperatures between June 20 and August 14, 1985.

Hours of daylight also was shown to be an important variable influencing daily height growth. All three *Salix* species examined during the 1985 growing season experienced the greatest increase in shoot height under conditions of long daylight hours. The only distinguishable difference between the species was the fact that a third variable, namely the previous day's evapotranspiration was entered into the multiple regression models of *S.purpurea* and *S.viminalis* daily height growth. However, this variable was not significant in influencing height growth of

S alba shoots when combined with the effects of maximum daily air temperature and the number of daylight hours. *S alba* clones also had the lowest number of independent climatic variables with significant linear relationships to daily height growth. This would appear to indicate that *S alba* clones were less influenced by the climatic variables included in this study than the other two species.

S viminalis clone 0683 was the most successful clone studied at Pasadena in terms of overall height growth during the 1985 growing season. The daily rate of height growth between June 20 and August 14 of *S.purpurea* clone 077 was greater than that of *S viminalis* and yet the final mean height of *S.purpurea* shoots was considerably less than that of *S viminalis*. This might be partially attributable to the ability of the *S viminalis* clone to continue higher rates of growth late in the growing season as most of the difference in height was realised after August 19, 1985. The *S.purpurea* clone and *S alba* clone 5023 showed a rapid decline in the rate of height growth after this date whereas the decline for *S viminalis* shoots was more gradual.

5.3.4. Summary and conclusions

The interpretation of the effect of climatic variables on the within season growth of *Salix* clones studied at the Pasadena nursery site during 1985 must be considered with respect to the fact that shoot height was an indicator variable of stem biomass accumulation. Measurements of leaf and root biomass increase were not considered and hence this study cannot quantify the degree that climate influences the overall biomass accumulation of these components. However, studies conducted in Sweden (Nilsson and Ericsson, 1986) indicate a strong relationship between shoot height and stem dry weight and therefore it was assumed that shoot height was an effective indicator of stem-biomass growth. The measurements of shoot base diameter could not be included in the final analysis due to the non-significant relationships found between daily base diameter increment change and the climate variables recorded.

The principle difficulty in assessing the influence of climate on growth of plants under natural conditions is the unknown effect of the interaction of environmental factors on the physiological and metabolic processes involved in growth. A preferable method of assessing the response of plants to climate under field conditions might be to model the physiological plant processes through variables derived from climate measurements. Byrne *et al* (1986) modeled the above ground monthly biomass increments of *Pinus radiata* by assuming that dry matter production within a given time interval was proportional to the amount of short-wave radiation absorbed by the canopy. Other climate variables were considered as indices governed by the limitations they would theoretically impose on maximum rates of photosynthesis. Booth and Ryan (1985) advocate the use of derived weather variables in the form of indices rather than original variables such as rainfall and mean temperature. The two methods were compared by performing two separate step-wise multiple regressions using original and derived climate variables. The variables derived from climatic indices of light, moisture and temperature accounted for a greater percentage of the variance in monthly base diameter growth of plantation grown Hoop pine in Australia than did original climatic variables.

The climate variables determined to be influential in determining daily height growth of the *Salix* species studied during the 1985 growing season, namely, maximum daily air temperature, hours of daylight and daily total evapotranspiration, re-affirm the choice of important variables included in growth models such as Eckersten's (1985) model of willow growth in an energy plantation environment. Eckersten was able to effectively estimate the within-season pattern of above ground biomass accumulation of a *Salix viminalis* clone by modeling of the process of photosynthesis as a function of light utilization by the canopy. A "water-growth factor" and "temperature function" were considered due to their potential influence on overall growth as a function of photosynthesis. The daily height growth of willow species at Pasadena, Newfoundland was affected by climate variables that would influence the main components in Eckersten's model. Models such as this are useful in that they attempt to explain growth through the physiological processes that result in biomass accumulation. The advantage of their use means that eventually it would be possible to predict the potential biomass production of plantation sites based on relatively simple and easily attainable measurements of climate.

Acknowledging the potential superiority of climate-based growth models, the results of this study are not without use. The weather of the 1985 growing season (May to September) was typical for the region when compared to the long term climate normals (Atmospheric Environment Service of Environment Canada, 1985) for the Deer Lake climatological station. The mean air temperature of the 1985 growing season (May to September) was identical (12.5 °C) when compared to the long term record for 1951 to 1980. Mean maximum and minimum air temperatures were within 0.4 °C of the long term means. Precipitation during the 1985 growing season was 49 mm (12%) greater than the long term average which re-affirms the final conclusion that water available for the growth of the willow species examined during the 1985 growing season was adequate, and therefore, potential water deficit conditions at the Pasadena nursery site were extremely infrequent.

Energy plantation forestry appears well suited to boreal climates due to the positive influence of long days on the daily height growth of the willow species examined during the 1985 growing season. It would be beneficial to examine the record for solar radiation when considering sites for *Salix* energy plantations as regions which experience a relatively high frequency of clear days during the growing season would have the potential of maintaining high rates of daily growth providing other environmental factors were not limiting. The island portion of the province of Newfoundland supports only one climatological station (St.John's West) which records observations of global radiation, while observations of sunshine duration and mean cloudiness during the summer months are recorded at ten climatological stations on the island (Banfield, 1981). Estimated averages of global radiation for these ten stations, empirically derived from cloud and sunshine observations, are also published by the Atmospheric Environment Service of Environment Canada (McKay and Morris, 1985). Those coastal sites which experience frequent occurrences of fog during the summer months would be unlikely to support maximum rates of growth in the willow species examined in this study, not only due to the infrequency of days with clear sky conditions, but also due to the cooler air temperatures associated with foggy environments.

The maximum production of biomass in willow energy plantations will be realised at sites which make best use of the energy available for photosynthesis by avoiding water deficit conditions that may be associated with high rates of evapotranspiration. This may be overcome through the choice of sites with adequate amounts of rainfall during the growing season or the use of irrigation under conditions of low precipitation.

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Appendix A

Energy Balance and Solar Radiation Data

Table A-1: Dates (*) when energy balance and solar radiation data were collected.

Julian Day	Date	Energy Balance Data	Solar Radiation Data
171	June 20		*
172	21		*
173	22	*	*
174	23	*	*
175	24		*
176	25	*	
177	26	*	
178	27	*	
179	28		
180	29		
181	30		
182	July 1	*	
183	2	*	
184	3	*	
185	4	*	
186	5	*	
187	6	*	
188	7	*	
189	8	*	
190	9	*	
191	10	*	
192	11	*	
193	12	*	
194	13		
195	14	*	
196	15	*	
197	16	*	*
198	17		*
199	18		*
200	19		*
201	20		*
202	21		*

Julian Day	Date	Energy Balance Data	Solar Radiation Data
203	July 22		*
204	23		*
205	24		*
206	25		*
207	26	*	*
208	27	*	*
209	28	*	*
210	29	*	*
211	30		*
212	31		*
213	Aug. 1		*
214	2		*
215	3		
216	4		
217	5		*
218	6	*	*
219	7	*	
220	8	*	*
221	9	*	*
222	10	*	
223	11	*	*
224	12	*	*
225	13	*	*
226	14	*	*

Appendix B

Calculations and Data Used in Chapter 3

B.1. Conversion of net and incoming solar radiation data.

1. Conversion of net radiation data collected by the energy balance measurement system.

Original values: hourly average net radiation in W m^{-2}.

$$W\ m^{-2} \div 697.8 = langleys\ min^{-1}$$
$$langleys\ min^{-1} \times 0.04186 = MJ\ m^{-2}\ min^{-1}$$
$$MJ\ m^{-2}\ min^{-1} \times 60 = MJ\ m^{-2}\ hour^{-1}$$

Hourly values of net radiation in MJ m^{-2} h^{-1} from the hour ending 07:00 to the hour ending 06:00 the proceeding day were added to give daily total net radiation in MJ m^{-2} d^{-1}.

2. Conversion of incoming solar radiation data measured by the Matrix Inc. pyranometer.

Original values: hourly readings of solar radiation data in millivolts.

$$millivolts \times 0.0194 + 0.099 = langleys\ min^{-1}\ (Matrix\ Inc.)$$
$$langleys\ min^{-1} \times 0.04186 = MJ\ m^{-2}\ min^{-1}$$
$$MJ\ m^{-2}\ min^{-1} \times 60 = MJ\ m^{-2}\ h^{-1}$$

Hourly values of solar radiation in MJ m^{-2} h^{-1} from 06:00 hours to 21:00 hours daily were added to give daily total incoming solar radiation in MJ m^{-2} d^{-1}. The hours included in determining the daily total of solar radiation were based on local times of sunrise and sunset.

B.2. Comparison of calculated and measured daily net radiation, June 20 to August 14, 1985, at the Pasadena nursery site.

A fitted least-squares regression with an intercept of zero was performed using thirteen days when both net and solar radiation data were available. The R-square value was 97 % and the standard error of the estimation was 1.84 MJ m^{-2} d^{-1} A scatterplot of the data and the regression line with 95% confidence intervals is shown in Figure B-1. The model was not as accurate at predicting low values of daily total net radiation as it was at predicting high values. Values of daily total net radiation below 7 MJ m^{-2} d^{-1} were consistently over-estimated by the model.

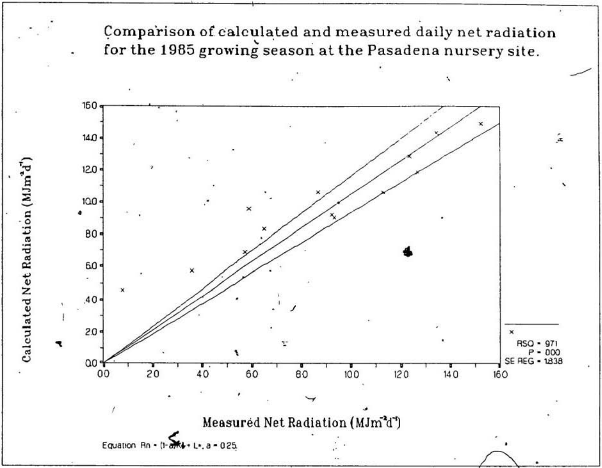

Figure B-1: Comparison of calculated and measured daily total net radiation, June 20 to August 14, 1985 at the Pasadena nursery site.

B.3. Regression of daily maximum and minimum air temperature from the Deer Lake climatological station and daily total net radiation at the Pasadena nursery site.

A multiple regression of measured daily total net radiation at the Pasadena nursery site on daily values of maximum and minimum air temperature at the Deer Lake climatological station produced a multiple correlation co-efficient of 0.86 and a standard error of the estimate of 1.85. The F ratio (regression mean square/error mean square) was significant at the 0.001 level (N=51). The tolerance value for maximum and minimum air temperature was 0.89, indicating a low level of correlation between the independent variables. The resulting equation was as follows:

$$Rn = -1.82 + 0.66 \; (\; T_{max} \;) - 0.27 \; (\; T_{min} \;).$$

B.4. The derivation of the co-efficient b for the calculation of the soil limited rate of transpiration.

The model used to predict daily transpiration (E_T) as the lesser of E_{max} (the energy limited rate) or E_s (the soil limited rate), assumed that a linear relationship existed between the soil limited rate of transpiration and the fraction of extractable water in the root zone, θ_e[2]. The use of the model requires a critical value of the amount of extractable water in the root zone (θ_{ec}), below which the amount of extractable water is not enough to maintain daily evapotranspiration at the energy limited rate. There will be a unique value of θ_{ec} for every value of E_{eq} (the equilibrium rate of evapotranspiration)[3]. Figure B-2 displays the ratio of the fraction of extractable water in the root zone to the equilibrium rate of evapotranspiration ($\frac{\theta_e}{E_{eq}}$), versus the ratio of the actual rate of daily transpiration (E_T)[4] to the equilibrium rate of evapotranspiration ($\frac{E_T}{E_{eq}}$).

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[2] see equation 3-9

[3] see equation 3-7

[4] E_{max} or E_s

The plotting of the fraction of available water in the root zone and the daily rate of evapotranspiration as ratios of the equilibrium rate of evapotranspiration creates two distinct lines which intersect at $\frac{\theta_{ec}}{E_{eq}} = \frac{\alpha}{b}$. It follows that when $\frac{\theta_{ec}}{E_{eq}} > \frac{\alpha}{b}$, transpiration would occur at the energy limited (E_{max}) rate and when $\frac{\theta_{ec}}{E_{eq}} < \frac{\alpha}{b}$, transpiration would occur at the soil limited (E_s) rate.

A value for volumetric soil water content (θ), is needed where the water becomes less easily extractable as a result of the relatively low amount of water in the soil. Figure B-3 displays the soil moisture retention of a typical sandy loam soil as a function of volumetric soil water content.

The soil moisture retention, or soil water potential (ψ), at various values of water content was calculated using Clapp and Hornberger's (1978) equation:

$$\psi = \psi_e \ (\theta \ / \ \theta_s \ )^{-m}$$

where: ψ is the soil water potential in bar,

$\psi_e = -0.012$ is the assumed saturation water potential in bar,

θ is the volumetric soil water content (dimensionless),

$\theta_s = 0.45$ is the assumed total porosity of the soil (dimensionless),

and $m = 5.30$ is an empirical coefficient (dimensionless).

The assumed values are given by Clapp and Hornberger (ibid) for a typical sandy loam soil.

A soil water potential of -5.0 bar was assumed to be the value below which water would be less easily extractable by the plant. This value was thought to be a reasonable estimate based on the supposed efficiency of willow roots at extracting water from the soil. The volumetric water content of the soil at -5 bar potential is 0.145 and the fraction of extractable water in the root zone (θ_{ec}) is 0.18[5].

On Julian day 203 a maximum value of the equilibrium rate of evapotranspiration (E_{eq}), of 3.45 mm occurred. It was assumed $E_{max} = E_s$ when $\frac{\theta_{ec}}{E_{eq}} = \frac{\alpha}{b}$. Substituting the assumed critical value of $\theta_{ec} = 0.18$ and $\alpha = 1.26$, the coefficient b is equal to 24 mm d^{-1}.

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[5] calculated using equation 3-9

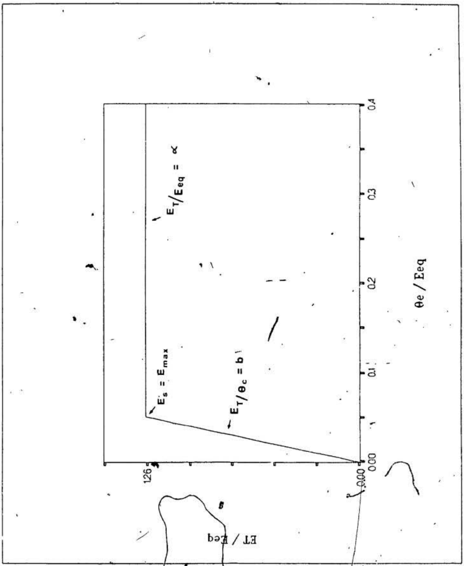

Figure B-2: The ratio of the fraction of extractable water in the root zone to the daily equilibrium rate of evapotranspiration versus the ratio of the actual rate of daily evapotranspiration to the daily equilibrium rate of evapotranspiration.

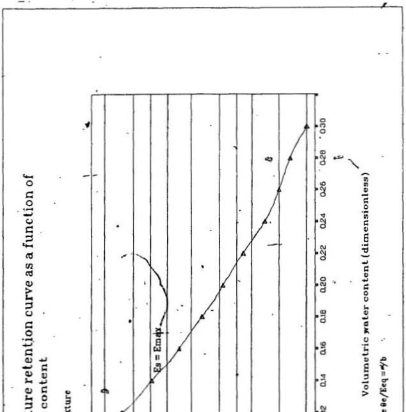

Figure B-3: Soil moisture potential as a function of soil water content for a typical sandy loam soil

B.5. Calculation of the early season water balance, May 14 to June 19, 1985.

Table B-1: Temperature dependent values used in the calculation of the energy limited rate of evapotranspiration May 14 (JD 134) to June 19 (JD 170), 1985.

Julian Day	T_{mean} °C	L_v MJ kg^{-1}	s kPa °C
134	3.3	2.502	0.0539
135	5.5	2.495	0.647
136	3.0	2.502	0.0537
137	6.0	2.495	0.0647
138	8.5	2.488	0.0775
139	14.5	2.471	0.1098
140	8.8	2.488	0.0775
141	11.8	2.481	0.0924
142	13.3	2.478	0.0979
143	11.5	2.481	0.0924
144	9.5	2.485	0.0822
145	9.8	2.485	0.0822
146	9.0	2.488	0.0775
147	9.0	2.488	0.0775
148	7.3	2.492	0.0687
149	7.0	2.492	0.0687
150	8.0	2.488	0.0730
151	7.8	2.488	0.0730
152	13.0	2.478	0.0979
153	12.5	2.478	0.0979
154	15.5	2.471	0.1161
155	14.0	2.476	0.1037
156	13.3	2.478	0.0979
157	7.0	2.492	0.0687
158	11.0	2.481	0.0872
159	10.0	2.485	0.0822
160	12.5	2.478	0.0979
161	7.5	2.488	0.0730

Julian Day	T_{mean} °C	L_v MJ kg^{-1}	$_s$ kPa °C
162	7.3	2.492	0.0687
163	6.5	2.492	0.0687
164	9.5	2.485	0.0822
165	9.0	2.488	0.0775
166	12.0	2.481	0.0924
167	12.0	2.481	0.0924
168	12.5	2.478	0.0979
169	15.8	2.471	0.1161
170	10.0	2.485	0.0822

Table B-2: Values used in the calculation of the energy limited rate of evapotranspiration May 14 (JD 134) to June 19 (JD 170), 1985.

Julian Day	T_{min} °C	T_{max} °C	R_n $MJm^{-2}d^{-1}$	G $MJm^{-2}d^{-1}$	E_{max} $mm\ d^{-1}$
134	-2.5	9.0	4.80	1.20	0.82
135	0.0	11.0	5.44	1.36	1.02
136	-1.0	7.0	3.07	0.77	0.52
137	-4.0	16.0	9.82	2.46	1.84
138	2.5	14.5	7.07	1.77	1.45
139	8.0	21.0	9.88	2.47	2.36
140	6.0	1.5	4.15	1.04	0.85
141	4.0	19.5	9.97	2.49	2.22
142	5.0	23.5	12.88	3.22	2.93
143	6.0	17.0	7.78	1.95	1.73
144	-1.0	20.0	11.65	2.91	2.46
145	-1.0	20.5	11.98	3.00	2.53
146	0.5	17.5	9.59	2.40	1.97
147	4.0	14.0	6.34	1.59	1.30
148	-2.5	17.0	10.08	2.52	1.95
149	4.0	10.0	3.70	0.93	0.71
150	2.0	14.0	6.88	1.72	1.37
151	-2.5	18.0	10.74	2.69	2.14
152	7.0	19.0	8.83	2.21	2.01
153	9.5	15.5	5.84	1.46	1.33
154	5.0	26.0	13.99	3.50	3.41
155	11.0	17.0	6.42	1.61	1.50
156	8.5	18.0	7.76	1.94	1.77
157	4.0	10.0	3.70	0.93	0.71
158	4.0	18.0	8.98	2.25	1.95
159	8.0	12.0	3.94	0.99	0.83
160	2.0	23.0	12.82	3.21	2.92
161	5.0	10.0	3.43	0.86	0.68
162	4.5	10.0	3.56	0.89	0.69
163	4.0	9.0	3.04	0.76	0.59
164	0.0	19.0	10.72	2.68	2.26

Julian Day	T_{min} °C	T_{max} °C	R_n $MJm^{-2}d^{-1}$	G $MJm^{-2}d^{-1}$	E_{max} mm d^{-1}
165	7.5	10.5	3.08	0.77	0.63
166	6.0	18.0	8.44	2.11	1.88
167	5.5	18.5	8.90	2.23	1.98
168	2.0	23.0	12.82	3.21	2.92
169	9.0	22.5	10.60	2.65	2.58
170	4.0	16.0	7.66	1.92	1.61

Table B-3: Water Balance of the top 30 cm of the soil, May 14 (JD 134) to June 19 (JD 170), 1985.

Julian Day	Soil Water Content mm	θ	θ_e	E_s mm d^{-1}	E_{max} mm d^{-1}	Ppt. mm d^{-1}	Change in Soil Water Content mm d^{-1}
134	60.0	0.30	1.00	24.00	0.82		-0.82
135	59.2	0.30	1.00	24.00	1.02		-1.02
136	58.2	0.29	0.95	22.80	0.52		-0.52
137	57.7	0.29	0.95	22.80	1.84	5.0	+3.16
138	60.0	0.30	1.00	24.00	1.45	5.2	+3.75
139	60.0	0.30	1.00	24.00	2.36	1.4	-0.96
140	59.0	0.30	1.00	24.00	0.85	4.8	+3.95
141	60.0	0.30	1.00	24.00	2.22	3.5	+1.28
142	60.0	0.30	1.00	24.00	2.93	1.6	-1.33
143	58.7	0.29	0.95	22.80	1.73		-1.73
144	57.0	0.29	0.95	22.80	2.46		-2.46
145	54.4	0.27	0.84	20.16	2.53		-2.53
146	51.9	0.26	0.79	18.96	1.97	1.6	-0.37
147	51.5	0.26	0.79	18.96	1.30		-1.30
148	50.2	0.25	0.74	17.76	1.95	1.3	-0.65
149	49.6	0.25	0.74	17.76	0.71		-0.71
150	48.9	0.25	0.74	17.76	1.37	0.6	-0.77
151	48.1	0.24	0.68	16.32	2.14	1.0	-1.14
152	47.0	0.24	0.68	16.32	2.01	3.0	+0.99
153	46.0	0.23	0.63	15.12	1.33		-1.33
154	44.7	0.22	0.58	13.92	3.41		-3.41
155	41.3	0.21	0.53	12.72	1.50	14.8	+13.30
156	54.6	0.27	0.84	20.16	1.77		-1.77
157	52.8	0.26	0.79	18.96	0.71	37.5	+36.79
158	60.0	0.30	1.00	24.00	1.95	4.2	+2.25
159	60.0	0.30	1.00	24.00	0.83		-0.83
160	59.2	0.30	1.00	24.00	2.92	2.6	-0.32
161	58.9	0.29	0.95	22.80	0.68	3.4	+2.72
162	60.0	0.30	1.00	24.00	0.69	0.30	-0.39
163	59.6	0.30	1.00	24.00	0.59		-0.59

Julian Day	Soil Water Content mm	θ	θ_e	E_s mm d^{-1}	E_{max} mm d^{-1}	Ppt. mm d^{-1}	Change in Soil Water Content mm d^{-1}
164	59.0	0.30	1.00	21.00	2.26	1.2	-1.06
165	57.9	0.29	0.95	22.80	0.63	2.8	+2.17
166	60.0	0.30	1.00	24.00	1.88		-1.88
167	58.1	0.29	0.95	22.80	1.98		-1.98
168	56.1	0.28	0.90	21.60	2.92	6.5	+3.58
169	60.0	0.30	1.00	24.00	2.58	2.4	-0.18
170	59.3	0.30	1.00	24.00	1.61	14.2	+12.59

B.6. Calculation of the water balance of the soil, June 20 to August 14, 1985.

Table B-4: Values used in the calculation of net radiation using solar radiation data, June 20 (JD 171) to August 14 (JD 226), 1985.

Julian Day	$K\downarrow$ MJm^{-2}d^{-1}	$K\downarrow_{max}$ MJm^{-2}d^{-1}	e_a kPa	ϵ_a	T^4 K x 10^9	L^* MJm^{-2}d^{-1}	Rn MJm^{-2}d^{-1}
171	17.23	31.97	1.30	0.765	6.87	-3.84	9.08
172	20.95	30.84	1.03	0.739	6.52	-5.02	10.69
175	29.61	31.97	1.00	0.736	6.96	-7.13	15.08
198	9.18	30.77	1.63	0.793	6.90	-2.08	4.80
199	15.39	30.66	1.37	0.771	6.78	-3.46	8.08
200	15.39	30.56	1.51	0.783	6.87	-3.30	8.25
202	25.09	30.40	1.48	0.781	7.07	-5.23	13.59
203	27.35	30.28	1.55	0.787	7.36	-5.68	14.83
204	24.40	30.16	1.42	0.776	7.21	-5.36	12.94
205	28.20	30.04	1.35	0.769	7.23	-6.37	14.78
206	25.06	29.92	1.50	0.782	7.39	-5.50	13.29
211	9.54	29.24	1.50	0.782	6.94	-2.38	4.77
212	28.44	29.10	1.01	0.737	6.82	-7.30	14.03
213	16.89	29.02	1.16	0.752	6.95	-4.42	8.25
214	14.86	28.86	1.36	0.770	6.60	-3.46	7.50
217	22.70	28.40	1.71	0.799	7.18	-4.64	12.39

Table B-5: Values used in the calculation of net radiation using temperature data from the Deer Lake Meteorological Station, June 20 (JD 171) to August 14 (JD 226), 1985

Julian Day	T_{min} °C	T_{max} °C	Rn MJm^{-2}d^{-1}
179	5.0	28.5	15.64
180	7.5	19.0	8.69
181	6.0	19.0	9.10
194	5.5	22.5	11.54
201	12.0	19.0	7.48
215	7.0	26.5	13.78
216	10.0	27.5	13.63

Table B-6: Values used in the calculation of the Energy Limited Rate of Evapotranspiration, June 20 (JD 171) to August 14 (JD 226), 1985.

Julian Day	T_{mean} °C	L_v $MJkg^{-1}$	s kPa °C	Rn $MJm^{-2}d^{-1}$	G % of Rn	G $MJm^{-2}d^{-1}$	E_{max} mm d^{-1}
171	14.7	2.473	0.1098	9.08	25	2.27	2.17
172	11.0	2.483	0.0872	10.69	25	2.67	2.35
173	7.8	2.488	0.0730	9.22	25	2.31	1.84
174	10.8	2.481	0.0872	15.24	25	3.81	3.31
175	15.7	2.471	0.1161	15.08	25	3.77	3.66
176	14.6	2.473	0.1098	14.54	25	3.64	3.47
177	15.2	2.471	0.1098	14.02	25	3.51	3.35
178	15.9	2.469	0.1161	13.86	24	3.33	3.43
179	19.6	2.461	0.1448	15.64	24	3.75	4.19
180	11.2	2.483	0.0872	8.69	24	2.09	1.91
181	13.0	2.478	0.0979	9.10	23	2.09	2.13
182	14.7	2.473	0.1098	15.27	23	3.51	3.75
183	17.5	2.466	0.1298	15.80	23	3.63	4.13
184	19.7	2.461	0.1448	12.84	22	2.82	3.53
185	18.3	2.464	0.1298	8.38	22	1.84	2.22
186	16.1	2.466	0.1161	7.76	22	1.71	1.97
187	21.1	2.457	0.1528	13.97	21	2.93	3.96
188	17.4	2.466	0.1228	6.36	21	1.34	1.67
189	20.1	2.461	0.1448	10.89	21	2.29	3.03
190	18.2	2.466	0.1298	9.73	20	1.95	2.64
191	21.9	2.457	0.1612	14.20	20	2.84	4.14
192	22.1	2.457	0.1612	9.42	20	1.88	2.75
193	18.5	2.464	0.1371	11.56	19	2.20	3.24
194	15.2	2.473	0.1098	11.54	19	2.19	2.98
195	20.9	2.459	0.1528	12.40	19	2.36	3.60
196	17.8	2.466	0.1298	9.46	18	1.70	2.63
197	15.3	2.473	0.1098	0.78	18	0.14	0.20
198	15.1	2.473	0.1098	4.80	18	0.86	1.25
199	13.8	2.476	0.1037	8.08	17	1.36	2.07
200	14.7	2.473	0.1098	8.25	17	1.40	2.25
201	15.8	2.471	0.1161	7.48	17	1.27	2.02

Julian Day	T_{mean} °C	L_v MJkg^{-1}	s kPa °C	Rn MJm^{-2}d^{-1}	G % of Rn	G MJm^{-2}d^{-1}	E_{max} mm d^{-1}
202	16.8	2.469	0.1228	13.59	16	2.17	3.77
203	19.7	2.461	0.1448	14.83	16	2.37	4.35
204	18.2	2.466	0.1298	12.94	16	2.07	3.66
205	18.4	2.466	0.1298	14.78	15	2.22	4.23
206	20.0	2.461	0.1448	13.29	15	1.99	3.96
207	22.1	2.457	0.1612	12.35	15	1.85	3.83
208	17.5	2.466	0.1298	5.88	15	0.88	1.70
209	15.4	2.471	0.1098	13.44	15	2.02	3.64
210	19.0	2.466	0.1371	11.26	14	1.58	3.34
211	15.5	2.473	0.1161	4.77	14	0.68	1.33
212	14.2	2.476	0.1037	14.03	13	1.82	3.79
213	15.6	2.471	0.1161	8.25	13	1.07	2.33
214	11.9	2.481	0.0924	7.50	12	0.90	2.00
215	18.1	2.466	0.1298	13.78	12	1.65	4.11
216	19.3	2.464	0.1371	13.63	11	1.50	4.19
217	17.9	2.466	0.1298	12.39	11	1.36	3.75
218	21.7	2.457	0.1612	12.69	10	1.27	4.16
219	20.3	2.459	0.1448	9.33	10	0.93	2.96
220	20.0	2.459	0.1448	10.09	10	1.01	3.20
221	18.7	2.464	0.1371	5.73	10	0.57	1.78
222	19.6	2.461	0.1448	5.00	10	0.50	1.59
223	18.7	2.464	0.1371	8.66	10	0.87	2.69
224	18.4	2.464	0.1298	6.49	10	0.65	1.98
225	15.1	2.471	0.1098	9.32	10	0.93	2.67
226	11.6	2.481	0.0924	3.58	10	0.36	0.95

Table B-7: Water Balance of the top 20 cm of the soil, June 20 (JD-171) to August 14 (JD 226), 1985.

Julian Day	Soil Water Content mm	θ	θ_e	E_s mm d^{-1}	E_{max} mm d^{-1}	Ppt. mm d^{-1}	Change in Soil Water Content mm d^{-1}
171	60.0	0.30	1.00	24.00	2.17		-2.17
172	57.8	0.29	0.95	22.74	2.35	0.25	-2.10
173	55.7	0.28	0.90	21.60	1.84		-1.84
174	53.9	0.27	0.84	20.16	3.31		-3.31
175	50.6	0.25	0.74	17.76	3.66		-3.66
176	46.9	0.23	0.63	15.12	3.47		-3.47
177	43.4	0.22	0.58	13.92	3.35		-3.35
178	40.0	0.20	0.47	11.28	3.43		-3.43
179	36.6	0.18	0.37	8.88	4.19		-4.19
180	32.4	0.16	0.26	6.24	1.91	28.18	+26.27
181	58.7	0.29	0.95	22.74	2.13		-2.13
182	56.6	0.28	0.90	21.60	3.75		-3.75
183	52.8	0.26	0.79	18.06	4.13		-4.13
184	48.7	0.24	0.68	16.42	3.53		-3.53
185	45.2	0.23	0.63	15.12	2.22	0.50	-1.72
186	43.5	0.22	0.58	13.92	1.97		-1.97
187	41.5	0.21	0.53	12.72	3.96		-3.96
188	37.5	0.19	0.42	10.08	1.67	5.70	+4.03
189	41.5	0.21	0.53	12.72	3.03		-3.03
190	38.5	0.19	0.42	10.08	2.64		-2.64
191	35.9	0.18	0.37	8.88	4.14		-4.14
192	31.8	0.16	0.26	6.24	2.75	0.50	-2.25
193	29.6	0.16	0.21	5.04	3.24		-3.24
194	26.4	0.13	0.11	2.64	2.98		-2.64
195	23.8	0.12	0.05	1.20	3.60	0.50	-0.70
196	23.1	0.12	0.05	1.20	2.63		-1.20
197	21.9	0.11	0.00	0.00	0.20	7.60	+7.60
198	29.5	0.15	0.21	5.04	1.25	21.84	+20.59
199	50.1	0.25	0.74	17.76	2.07	2.79	+0.72
200	50.8	0.25	0.74	17.76	2.25	2.79	+0.54

Julian Day	Soil Water Content mm	θ	θ_e	E_s mm d^{-1}	E_{max} mm d^{-1}	Ppt. mm d^{-1}	Change in Soil Water Content mm d^{-1}
201	51.3	0.26	0.79	18.96	2.02	4.57	+2.55
202	53.9	0.27	0.84	20.16	3.77		-3.77
203	50.1	0.25	0.74	17.76	4.35		-4.35
204	45.8	0.23	0.63	15.12	3.66		-3.66
205	42.1	0.21	0.53	12.72	4.23		-4.23
206	37.9	0.19	0.42	10.08	3.96		-3.96
207	33.9	0.17	0.32	7.68	3.83		-3.83
208	30.1	0.15	0.21	5.04	1.70		-1.70
209	28.4	0.14	0.16	3.84	3.64		-3.64
210	24.8	0.12	0.05	1.20	3.34		-1.20
211	23.6	0.12	0.05	1.20	1.33	8.63	+7.43
212	31.0	0.16	0.26	6.21	3.79		-3.79
213	27.2	0.14	0.16	3.84	2.33	2.29	-0.04
214	27.2	0.14	0.16	3.84	2.00	9.14	+7.14
215	34.3	0.17	0.32	7.68	4.11		-4.11
216	30.2	0.15	0.21	5.04	4.19		-4.19
217	26.0	0.13	0.11	2.64	3.75		-2.64
218	23.4	0.12	0.05	1.20	4.16		-1.20
219	22.2	0.11	0.09	0.00	2.96		0.00
220	22.2	0.11	0.00	0.00	3.20		0.00
221	22.2	0.11	0.00	0.00	1.78	2.51	+0.76
222	23.0	0.12	0.05	1.20	1.59	1.27	+0.07
223	23.7	0.12	0.05	1.20	2.69		-1.20
224	22.5	0.11	0.00	0.00	1.98	4.57	+2.59
225	25.1	0.13	0.11	2.64	2.67	0.25	-2.42
226	22.7	0.11	0.00	0.00	0.95		-0.95

B.7. Daily measurements of wind speed, June 20 to August 14, 1985.

Table B-8: Daily mean values of wind speed in m sec^{-1}, June 20 to August 14, 1985.

Julian Day	Wind speed m sec^{-1}
171	0.8
172	0.2
173	0.5
174	0.3
175	0.5
176	0.3
177	0.3
178	0.2
179	0.3
180	0.2
181	0.3
182	0.3
183	0.3
184	0.6
185	0.6
186	0.2
187	0.6
188	0.2
189	0.8
190	0.9
191	0.8
192	1.8
193	0.9
194	0.5
195	1.2
196	1.1
197	0.5
198	0.6
199	0.3

Julian Day	Wind speed m sec^{-1}
200	0.3
201	0.5
202	0.6
203	0.8
204	0.9
205	1.2
206	1.7
207	1.1
208	1.4
209	1.8
210	0.8
211	0.8
212	0.6
213	0.5
214	0.9
215	0.8
216	0.6
217	0.2
218	0.6
219	0.3
220	0.3
221	0.3
222	0.3
223	0.8
224	0.3
225	0.6
226	0.5

Appendix C

Results of the linear least-squares regression of daily climatic variables and daily mean shoot height and base diameter increment change.

Table C-1: Results of regression of *Salix purpurea* daily shoot height increment change on daily values of climatic variables; t(0.001, 50) = 3.50.

Climatological Variable	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef.	t Value	Standard Error of the Estimate	Corr. Coeff. (r^2)
Mean air temp.	-0.04	0.172	0.042	4.07	0.99	0.25
Max. air temp.	-1.31	0.172	0.035	4.95	0.93	0.33
Min. air temp.	2.35	0.047	0.036	1.32	1.12	0.03
Range in air temp.	2.03	0.063	0.032	1.99	1.10	0.07
Soil temp. 10 cm	-1.84	0.266	0.084	3.15	1.01	0.17
Soil temp. 20 cm	-0.73	0.203	0.097	2.10	1.09	0.08
Soil temp. 30 cm	0.73	0.123	0.098	1.25	1.42	0.03
Vapour pressure deficit	1.89	1.756	0.460	3.82	1.00	0.23
Net radiation	1.29	0.152	0.039	3.90	1.00	0.23
Evapotranspiration	1.77	0.439	0.111	3.97	0.99	0.24
Soil water content	2.02	0.023	0.013	1.76	1.11	0.06
Water deficit	2.94	-0.275	0.202	-1.37	1.12	0.04
Wind speed	2.75	0.177	0.392	0.45	1.14	0.00
Hours of daylight	-15.42	1.172	0.244	4.81	0.94	0.32

Table C-2: Results of regression of *Salix pupurea* daily shoot height increment change on the previous day's values of climatic variables; t(0.001, 50) = 3.50.

Climatological Variables	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef.	t Value	Standard Error of the Estimate	Corr. Coeff. (r^2)
Mean air temp.	2.66	0.018	0.051	0.23	1.15	0.00
Max. air temp.	1.96	0.037	0.045	0.82	1.14	0.01
Min. air temp.	3.13	-0.025	0.036	-0.68	1.15	0.01
Range in air temp.	2.31	0.041	0.034	1.22	1.13	0.03
Soil temp. 10 cm	2.64	0.012	0.095	0.13	1.15	0.00
Soil temp. 20 cm	2.94	-0.005	0.103	-0.04	1.15	0.00
Soil temp. 30 cm	3.37	-0.030	0.101	-0.29	1.15	0.00
Vapour pressure deficit	2.67	0.340	0.531	0.64	1.15	0.01
Net radiation	1.44	0.135	0.042	3.18	1.05	0.17
Evapotranspiration	1.69	0.468	0.111	4.21	1.00	0.27
Soil water content	1.38	0.040	0.013	3.20	1.05	0.17
Water deficit	3.03	-0.589	0.190	-3.11	1.05	0.16
Wind speed	2.94	-0.122	0.397	-0.31	1.15	0.00
Hours of daylight	-16.73	1.250	0.256	4.90	0.94	0.33

Table C-3: Results of regression of *Salix viminalis* daily shoot height increment change on daily values of climatic variables; t(0.001, 50) = 3.50.

Climatological Variable	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef.	t Value	Standard Error of the Estimate	Corr. Coeff. (r^2)
Mean air temp.	0.52	0.135	0.040	3.46	0.91	0.19
Max. air temp.	-0.98	0.156	0.031	5.09	0.82	0.34
Min. air temp.	2.82	-0.002	0.032	-0.07	1.01	0.00
Range in air temp.	1.55	0.093	0.026	3.59	0.90	0.21
Soil temp. 10 cm	0.173	0.148	0.079	1.87	0.98	0.07
Soil temp. 20 cm	1.08	0.097	0.089	1.10	1.00	0.02
Soil temp. 30 cm	2.36	0.025	0.089	0.28	1.01	[illegible]
Vapour pressure deficit	1.81	1.767	0.39	4.52	0.85	0.29
Net radiation	0.97	0.176	0.031	5.75	0.78	0.40
Evapotranspiration	1.68	0.448	0.093	4.82	0.84	0.32
Soil water content	2.38	0.011	0.011	0.96	1.00	0.02
Water deficit	2.83	-0.139	0.181	-0.77	1.01	0.01
Wind speed	2.52	0.432	0.343	1.26	1.00	0.03
Hours of daylight	-10.52	0.853	0.232	3.68	0.90	0.21

Table C-4: Results of regression of *Salix viminalis* daily shoot height increment change on the previous day's values of climatic variables; t(0.001, 50) = 3.50.

Climatological Variable	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef.	t Value	Standard Error of the Estimate	Corr. Coeff. (r^2)
Mean air temp.	2.73	0.003	0.045	0.07	1.02	0.00
Max. air temp.	1.56	0.050	0.040	1.27	1.00	0.03
Min. air temp.	3.46	-0.062	0.031	-1.99	0.98	0.08
Range in air temp.	1.66	0.083	0.028	2.96	0.94	0.15
Soil temp. 10 cm	3.58	-0.045	0.084	-0.54	1.02	0.01
Soil temp. 20 cm	4.00	-0.069	0.090	-0.76	1.01	0.01
Soil temp. 30 cm	4.25	-0.085	0.88	-0.96	1.01	0.02
Vapour pressure deficit	2.34	0.779	0.458	1.70	0.99	0.06
Net radiation	1.06	0.164	0.034	4.83	0.84	0.32
Evapotranspiration	1.54	0.494	0.091	5.45	0.80	0.38
Soil water content	1.65	0.031	0.011	2.71	0.95	0.13
Water deficit	2.92	-0.463	0.171	-2.70	0.95	0.13
Wind speed	2.89	-0.174	0.351	-0.50	1.02	0.01
Hours of daylight	-11.04	0.885	0.246	3.60	0.91	0.21

Table C-5: Results of regression of *Salix alba* daily shoot height increment change on daily values of climatic variables; t(0.001, 50) = 3.50.

Climatological Variable	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef.	t Value	Standard Error of the Estimate	Corr. Coeff. (r^2)
Mean air temp.	0.30	0.140	0.043	3.21	1.01	0.17
Max. air temp.	-1.24	0.160	0.035	4.62	0.93	0.30
Min. air temp.	2.56	0.007	0.035	0.21	1.11	0.00
Range in air temp.	1.42	0.092	0.029	3.14	1.02	0.16
Soil temp. 10 cm	0.11	0.143	0.088	1.63	1.08	0.05
Soil temp. 20 cm	1.19	0.082	0.098	0.84	1.10	0.01
Soil temp. 30 cm	2.55	0.005	0.097	0.05	1.11	0.00
Vapour pressure deficit	1.56	1.958	0.428	4.57	0.93	0.29
Net radiation	1.15	0.144	0.038	3.76	0.98	0.22
Evapotranspiration	1.68	0.388	0.111	3.50	1.00	0.20
Soil water content	2.42	0.006	0.013	0.47	1.11	0.00
Water deficit	2.69	-0.186	0.199	-0.93	1.10	0.02
Wind speed	2.38	0.423	0.379	1.12	1.10	0.02
Hours of daylight	-11.96	0.094	0.255	3.66	0.99	0.21

Table C-6: Results of regression of *Salix alba* daily shoot height increment change on the previous day's values of climatic variables; t(0.001, 50) = 3.50.

Climatological Variable	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef.	t Value	Standard Error of the Estimate	Corr. Coeff. (r^2)
Mean air temp.	2.74	-0.008	0.049	-0.16	1.10	0.00
Max. air temp.	1.49	0.046	0.043	1.07	1.09	0.02
Min. air temp.	3.34	-0.067	0.034	-2.00	1.06	0.07
Range in air temp.	1.46	0.086	0.031	2.79	1.02	0.14
Soil temp. 10 cm	2.80	-0.011	0.091	-0.12	1.10	0.00
Soil temp. 20 cm	2.99	-0.022	0.098	-0.22	1.10	0.00
Soil temp. 30 cm	3.43	-0.047	0.096	-0.49	1.10	0.00
Vapour pressure deficit	2.13	0.856	0.496	1.73	1.07	0.06
Net radiation	1.00	0.153	0.039	3.97	0.959	0.24
Evapotranspiration	1.62	0.395	0.111	3.57	0.98	0.21
Soil water content	1.91	0.019	0.013	1.48	1.08	0.04
Water deficit	2.71	-0.332	0.193	-1.72	1.07	0.06
Wind speed	2.66	-0.085	0.380	-0.22	1.10	0.00
Hours of daylight	-11.61	0.910	0.269	3.38	0.99	0.19

Table C-7: Results of regression of *Salix purpurea* daily shoot base diameter increment change on daily values of climatic variables; t(0.001, 50) = 3.50.

Climatological Variable	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef.	t Value	Standard Error of the Estimate	Corr. Coeff. (r^2)
Mean air temp.	0.013	-0.0002	0.0001	-0.19	0.02	0.00
Max. air temp.	0.015	-0.0002	0.0009	-0.24	0.02	0.00
Min. air temp.	0.001	-0.0008	0.0007	-1.13	0.02	0.03
Range in air temp.	0.021	-0.0008	0.0007	-1.22	0.02	0.03
Soil temp. 10 cm	0.017	-0.0004	0.002	-0.21	0.02	0.00
Soil temp. 20 cm	0.019	-0.0005	0.002	-0.25	0.02	0.00
Soil temp. 30 cm	0.026	-0.0009	0.002	-0.44	0.02	0.00
Vapour pressure deficit	0.019	-0.015	0.011	-1.43	0.02	0.04
Net radiation	0.019	-0.0008	0.0009	-0.92	0.02	0.02
Evapotranspiration	0.008	0.0008	0.003	0.32	0.02	0.02
Soil water content	0.003	0.0002	0.0003	0.73	0.02	0.01
Water deficit	0.012	-0.008	0.004	-1.95	0.02	0.07
Wind speed	0.007	0.005	0.008	0.63	0.02	0.01
Hours of daylight	-0.106	0.007	0.006	1.21	0.02	0.03

Table C-8: Results of regression of *Salix purpurea* daily shoot base diameter increment change on the previous day's values of climatic variables; t(0.001, 50) = 3.50.

Climatological Variable	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef.	*t* Value	Standard Error of the Estimate	Corr. Coeff. (r^2)
Mean air temp.	-0.001	0.001	0.001	0.62	0.02	0.01
Max. air temp.	-0.015	0.001	0.001	1.13	0.02	0.03
Min. air temp.	0.010	-0.00003	0.0008	-0.03	0.02	0.00
Range in air temp.	0.002	0.0006	0.007	0.86	0.02	0.02
Soil temp. 10 cm	0.006	0.0003	0.0019	0.13	0.02	0.00
Soil temp. 20 cm	0.013	0.0002	0.0021	-0.09	0.02	0.00
Soil temp. 30 cm	0.019	-0.0005	0.0021	-0.25	0.02	0.00
Vapour pressure deficit	0.002	0.0134	0.0108	1.24	0.02	0.03
Net radiation	0.006	0.0015	0.0009	1.63	0.02	0.05
Evapotranspiration	0.006	0.0016	0.0027	0.60	0.02	0.01
Soil water content	0.016	0.0002	0.0003	0.81	0.02	0.01
Water deficit	0.008	0.007	0.004	1.77	0.02	0.06
Wind speed	0.012	-0.0038	0.0081	-0.47	0.02	0.00
Hours of daylight	-0.094	0.007	0.006	1.04	0.02	0.02

Table C-9: Results of regression of *Salix viminalis* daily shoot base diameter increment change on daily values of climatic variables; t(0.001, 50) = 3.50.

Climatological Variable	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef	t Value	Standard Error of the Estimate	Corr Coeff (r^2)
Mean air temp.	0.013	0.00003	0.0013	0.02	0.030	0.00
Max. air temp.	-0.001	0.006	0.001	0.53	0.03	0.01
Min. air temp.	0.010	0.0004	0.0010	0.39	0.03	0.00
Range in air temp.	0.014	0.000	0.000	0.00	0.03	0.00
Soil temp. 10 cm	0.033	-0.001	0.002	-0.45	0.03	0.00
Soil temp. 20 cm	0.039	-0.001	0.003	-0.54	0.03	0.01
Soil temp. 30 cm	0.038	-0.001	0.003	-0.53	0.03	0.01
Vapour pressure deficit	0.014	-0.001	0.014	-0.08	0.03	0.00
Net radiation	0.001	0.001	0.001	1.05	0.03	0.02
Evapotranspiration	0.010	0.002	0.003	0.48	0.03	0.00
Soil water content	-0.000	0.0004	0.0003	1.11	0.03	0.02
Water deficit	0.013	0.004	0.005	0.76	0.03	0.01
Wind speed	0.014	0.0005	0.010	0.05	0.03	0.00
Hours of daylight	-0.118	0.008	0.008	1.10	0.03	0.02

Table C-10: Results of regression of *Salix viminalis* daily shoot base diameter increment change on the previous day's values of climatic variables; t(0.001, 50) = 3.50.

Climatological Variable	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef.	t Value	Standard Error of the Estimate	Corr. Coeff. (r^2)
Mean air temp.	0.009	0.0003	0.0013	0.20	0.03	0.00
Max. air temp.	-0.001	0.0006	0.0012	0.48	0.03	0.00
Min. air temp.	0.031	-0.0017	0.0009	-1.84	0.03	0.06
Range in air temp	-0.011	0.0018	0.0008	2.12	0.03	0.08
Soil temp. 10 cm	-0.016	0.0017	0.0024	0.68	0.03	0.01
Soil temp. 20 cm	-0.017	0.0017	0.0026	0.64	0.03	0.01
Soil temp. 30 cm	-0.002	0.0009	0.0026	0.33	0.03	0.00
Vapour pressure deficit	0.001	0.021	0.013	1.60	0.03	0.05
Net radiation	-0.003	0.0015	0.0010	1.25	0.03	0.03
Evapotranspiration	0.007	0.0025	0.0033	0.76	0.03	0.01
Soil water content	0.002	0.0003	0.0004	0.82	0.03	0.01
Water deficit	0.012	0.033	0.0050	0.62	0.03	0.01
Wind speed	0.009	0.0067	0.0102	0.66	0.03	0.01
Hours of daylight	-0.089	0.007	0.008	0.82	0.03	0.01

Table C-11: Results of regression of *Salix alba* daily shoot base diameter increment change on daily values of climatic variables; t(0.001, 50) = 3.50.

Climatological Variable	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef.	t Value	Standard Error of the Estimate	Corr. Coeff. (r^2)
Mean air temp.	-0.001	0.0009	0.0010	0.88	0.02	0.02
Max. air temp.	-0.022	0.0015	0.0009	1.74	0.02	0.06
Min. air temp.	0.009	0.0005	0.0007	0.72	0.02	0.01
Range in air temp	0.008	0.0005	0.0007	0.69	0.02	0.01
Soil temp. 10 cm	0.011	0.0002	0.0016	0.12	0.02	0.00
Soil temp. 20 cm	0.019	-0.0003	0.0023	-0.13	0.02	0.00
Soil temp. 30 cm	0.022	-0.0004	0.0019	-0.21	0.02	0.00
Vapour pressure deficit	0.015	-0.0013	0.0110	-0.12	0.02	0.00
Net radiation	0.010	0.0005	0.0009	0.51	0.02	0.01
Evapotranspiration	0.005	0.0042	0.0030	1.40	0.02	0.04
Soil water content	0.008	0.0002	0.0003	0.60	0.02	0.01
Water deficit	0.016	-0.006	0.004	-1.45	0.02	0.04
Wind speed	0.017	-0.004	0.008	-0.43	0.02	0.00
Hours of daylight	-0.106	0.077	0.006	1.28	0.02	0.03

Table C-12: Results of regression of *Salix alba* daily shoot base diameter increment change on the previous day's values of climatic variables; $t(0.001, 50) = 3.50$.

Climatological Variable	Intercept	Regr. Coeff.	Standard Error of the Reg. Coef.	t Value	Standard Error of the Estimate	Corr. Coeff. (r^2)
Mean air temp.	0.015	-0.00005	0.0010	-0.05	0.02	0.00
Max. air temp.	-0.007	0.0008	0.0009	0.93	0.02	0.02
Min. air temp.	0.022	-0.0008	0.0007	-1.08	0.02	0.02
Range in air temp.	-0.002	0.0012	0.0007	1.69	0.02	0.06
Soil temp. 10 cm	0.015	-0.00007	0.0019	-0.04	0.02	0.00
Soil temp. 20 cm	0.010	0.0002	0.0021	0.11	0.02	0.00
Soil temp. 30 cm	0.010	0.0002	0.0021	0.10	0.02	0.00
Vapour pressure deficit	0.007	0.0119	0.0107	1.11	0.02	0.03
Net radiation	0.003	0.0011	0.0009	1.13	0.02	0.03
Evapotranspiration	0.015	-0.0004	0.0029	-0.14	0.02	0.00
Soil water content	0.008	-0.00015	0.00028	0.52	0.02	0.01
Water deficit	0.011	0.0096	0.0040	2.39	0.02	0.10
Wind speed	0.015	-0.0021	0.0081	-0.26	0.02	0.00
Hours of daylight	-0.090	0.0071	0.0066	1.08	0.02	0.02