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STRESS, STRAIN, AND INJURY: SCOTS PINE TRANSPLANTS FROM LIFTING TO ACCLIMATION ON THE PLANTING SITE

METSÄNVILJELYTAIMIEN VAURIOITUMINEN NOSTON JA ISTUTUKSEN VÄLILLÄ

Pekka Kauppi

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Pekka Kauppi

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METSÄNVILJELYTAIMIEN VAURIOITUMINEN NOSTON JA ISTUTUKSEN VÄLILLÄ

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This paper is the final report of a study on the damage of tree transplants induced before the trees are planted in the field. The injury development is viewed as a transient rather than a "step-like" process. The main objective of the study is to develop concepts and methods for recognizing and analysing the dynamic aspects of that process. The report consists of three parts: i) characterization of the environments to which the plants are exposed, ii) theoretical part of model development, and iii) experiments with barerooted Scots pine transplants in which the model was applied.

The results of the first part of the report indicate fast temporal variation of the environmental stress factors, and a slow response of the plant in terms of visible injury symptoms. A model is developed in the second part of the report for analysing the relationship between the fast stress variables and the slow injury variables. The model is employed in the third part of the study for developing experiments in which the transplants were subjected to different stress conditions. The conclusions emphasize the hazardous role of root desiccation. Similar injury development was observed over a range of different planting sites. Controlling high temperatures during the transportation and storage of the plants was introduced as an indirect method for avoiding the risk of root desiccation.

Raportissa esitetään metsäpuiden taimien kuljetus- ja varastointivaurioita koskevan tutkimuksen päätulokset. Taimen vaurioitumista ei kuvata äkillisenä kertatapahtumana vaan yhtäjaksoisena prosessina, joka etenee vaihtelevalla nopeudella. Tutkimuksen päätavoitteena on kehittää käsitteitä ja menetelmiä, joilla voidaan kiinnittää huomiota vaurioitumisprosessin yhtäjaksoiseen luonteeseen sekä eritellä vaurion voimakkuuteen vaikuttavia tekijöitä. Raportin ensimmäisessä jaksossa esitetään kuljetus- ja varastointioloja koskevia mittaustuloksia. Toisessa jaksossa kehitetään käsitteitä ja menetelmiä. Kolmannessa jaksossa esitetään paljasjuuristen männyntaimien vaurioitumista selvittävä koesarja.

Taimien välittömästä ympäristöstä mitattujen rasitustekijöiden todettiin vaihtelevan nopeasti tunnista toiseen, kun sensijaan taimen vaurioreaktiot saatettiin havaita vasta viikkojen kuluttua. Nopeiden ja hitaiden muuttujien toisiinsa rinnastamista varten kehitettiin teoreettinen malli, jonka sovellutuksena laaditun koesarjan perusteella tärkeäksi vaurioitumisen aiheuttajaksi todettiin juuriston kuivuminen. Monilla erilaisilla istutuspaikoilla havaittiin juurten kuivaamiskäsittelyn seurauksena olennaisesti yhdenmukainen vauriokehitys.

Tutkimuksen päätuloksena pidetään luvussa 3. kuvattua taimien vaurioitumisen teoreettista mallia, johon yksityiskohtaiset kokeet perustuvat. Koetulosten pohjalta voidaan eräät tekijät todeta käytännön metsänviljelyn onnistumista ajatellen verrattain yhdentekeviksi kun sen sijaan juuriston kuivumisvaaraa on pidettävä erittäin huomionarvoisena. Juuriston kuivumista voidaan käytännössä estää mm. välttämällä korkeita lämpötiloja varastoinnin ja kuljetuksen aikana.

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I had the opportunity to extend my research within forest regeneration until 1982, several years beyond the original deadline. During those years I felt minimum pressure for short-term accomplishments and I had an ideal opportunity to concentrate my efforts on this study. Innumerable discussions with colleagues, especially within the Primary Production Group, stimulated the research in many ways. For this stimulus I am particularly grateful to two persons, Dr. Pertti Hari and Mr. Heikki Smolander.

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Helsinki, 3:rd of July 1984

Pekka Kauppi

1. INTRODUCTION

1.1. Tree planting as large scale activity

In 1981, about 240 million forest plants were used in Finland for forest regeneration. The plants were distributed and planted over a reforestation area of 141 000 hectares. More than half of all the plants were barerooted Scots pine transplants (Yearbook . . . , 1981; Yearbook . . . , 1982). Statistics of this kind are not available on a worldwide basis. However, a recent questionnaire by Tinus (1983) indicates that in 15 countries which practice intensive forestry, more than 4 billion trees are planted annually. Of this stock, over 80 per cent are barerooted plants. There are indications that barerooted plants may continue to be competitive (Harstela & Tervo, 1983).

On a small, experimental scale, by handling the transplant carefully, it is possible to plant a tree with a very high probability of success (cf. Huuri, 1972). But in large-scale reforestation programs, due to the heavy work load, such careful handling of every plant cannot be arranged. Given the economic constraints, this would not even be desirable. It is not surprising, therefore, that substantial plant losses have been recorded in most, if not all, of the regeneration inventories (Yli-Vakkuri et al. 1969; Leikola et al. 1977; Rautiainen & Räsänen, 1980; Pelkonen et al. 1982; and Kinnunen & Nerg, 1983). In some cases, less than half of the planted trees have survived long enough to produce marketable timber. Fortunately, as shown by Leikola et al. (1977), such losses are partially compensated by naturally regenerated saplings.

Plant loss in forest regeneration programs are to some extent acceptable because of the cost constraints of the large scale effort. There is a need, however, to continuously uppgrade regeneration methods so as to improve results and to decrease costs. In such efforts it is important to bear in mind the whole process of regeneration from the seed to the established new stand (Österström et. al 1974; Räsänen, 1981; Parviainen & Lappi, 1983). Räsänen (1980) divides this process into the following phases:

000 Seed formation
00 Collection of seed
0 Storage of seed
1 Sowing phase
2 Germination phase
3 Germling phase
4 Seedling phase
5 Transplanting phase
6 Transplant phase
7 Transfer (lifting, packing, transport) phase
8 Plantig phase
9 Planting shock phase
10 Weed phase
11 Snow limit phase
12 Establishment phase
13 Competition phase (differentiation into crown classes).

An effective way to uppgrade planting practices is first to identify the weakest links of the planting process and then to look for improvements in these critical phases. As pointed out by Yli-Vakkuri (1957), a particularly critical period for baretooted plants occurs between lifting and the weed phase. Between lifting and planting the roots are detached from the soil, so that the transplant is subjected to an exceptional environment with respect to its evolutionary history. Therefore, transplants deserve particular attention and care during that period. This, however, is not easy to arrange in large scale programs. Especially this is difficult in northern latitudes, where the favorable planting season peaks within a few weeks after the frost melts (see Heikinheimo, 1954). The heavy work load does not permit wide safety margins in plant treatment. The planting phase is followed by the "planting shock phase" which also could be called acclimation phase. An important part of this phase is root development (Heikinheimo, 1941; Stupendik and Shepherd, 1980). Acclimation also takes place elsewhere in the plant. The whole plant must adjust its structure and functioning to the altered environment in respect to moisture, nutrients, temperature, solar radiation and other factors. The particularly critical period terminates when the acclimation processes have caused the stock to resemble a naturally regenerated stand with comparable site factors and genotype.

The damage to the plant is difficult to detect within the critical phases of plant transportation, storage, and planting. Both conifers and broadleaved plants in the leafless stage are slow in developing visible symptoms so that the damage often remains latent for several weeks. Due to this delay, weak plants may be introduced into the expensive planting phase, as they still look vigorous. Moreover, also due to the delay, it is difficult to keep track of where, when and why the damage was induced. Therefore, the mistake is likely to be repeated the following year. As the causal relationships are not self-evident, intensive research is required for improving the understanding of the processes preceding injury.

A good deal of literature already exists on conifer transplants, spanning from phase 7 to phase 9 of the above classification. The transfer phase, for example, has been studied by Yli-Vakkuri (1957), the planting phase by Huuri (1972), and the acclimation phase by Hallman et al. (1978). In field studies the stock has been subjected to unfavorable conditions before planting, and the effect of this treatment has been demonstrated in terms of growth and survival which are measured after a prolonged period of time, so that the potential damage has had time to manifest itself. Damage due to mistratment has been reported by Hedemann-Gade (1949, 1960), Yli-Vakkuri (1957), Herrman (1962, 1964, 1967), Mullin (1971), Liptak (1970), and Huuri (1972).

The understanding of the process of damage has improved with physiologically oriented research which has been increasingly introduced into this field since the late 1960s. The concept "planting shock" has been used in many physiologically oriented studies. This concept encompasses the typical physiological processes of a recently planted transplant, as compared to those of an otherwise comparable tree which has been regenerated naturally. The "planting shock" has often been associated with water deficit: The root systems of the plants are not able to absorb enough water after transplanting. A water deficit begins to manifest itself, CO_2-uptake is inhibited, and the increase in dry matter is reduced due to the lack of photosynthates (Gürth, 1969; see also Tranquillini, 1973; Havranek and Tranquillini, 1972; v. Lüpke, 1973; Havranek, 1975; Hallman et al. 1978; and Korpilahti, 1982).

Planting itself can hardly alter the physiology of the plant in a way which would induce large scale damage (e.g. Huuri, 1972). Physiologically oriented research lends support to this view (Hallman et al. 1978; Korpilahti, 1982). "Planting shock" thus appears to be triggered by mistreatment partially in the planting phase, but partially already in the phases of storage and transportation.

1.2. Objectives and structure of the study

This study focuses on barerooted Scots pine transplants within the time period from lifting in the forest nursery to acclimation on the planting site. The objective of the study is to develop new research methods for analysing the responses of transplants to unfavourable environmental conditions. The intention is to describe potential injury development as a result of both environmental factors and plant internal factors. In particular, the main objective of the study is to develop concepts and methods for recognizing and analysing the dynamic aspects of injury development in tree transplants, which are key factors in this type of damage where there is a delay between inducing the damage and observing it. An additional objective is to apply the new methods to empirical data in order to make a contribution to the information regarding the relative importance of selected factors affecting the damage.

This study report consists of three parts. Section 2 is a characterization of the environments to which plants are exposed. Special emphasis in this section is given to the temporal variation of the environmental factors. Next, Section 3 is the theoretical part of the study which is devoted to the development of the new concepts and methods for analysing the dynamic aspects of injury development. Requirements for these considerations are largely derived from the features of the environment as recorded in Section 2. Finally, Section 4 reports empirical experiments to which the new concepts and methods were applied. Several potential causes of injury are examined. These factors are tentatively ranked in order of their importance. An empirical model is developed for predicting the injury in transplants with roots exposed to the open air.

2. TEMPORAL VARIATION OF ENVIRONMENTAL FACTORS: A COMPARISON OF TRANSPORTATION BAGS

2.1. Purpose of the comparison

Plant transportation bags are not recommended for storing plants for any prolonged period of time. Sometimes, perhaps due to the heavy work load, this recommendation is overlooked, and unloading of the plants from the bag is delayed. Under such circumstances the plants are subjected to rather extreme environmental conditions. The objective of this section is to describe the environmental conditions inside transportation bags in order to improve the understanding of extreme field conditions on barerooted plants. In particular, the main objective of this section is to describe the temporal variation of the environmental factors inside the bags. Such information is later utilized in the theoretical part of the study. An additional objective is to compare alternative bag types, and based on this comparison, to make recommendations for selecting an appropriate bag for plant transportation. Special attention is given to controlling maximum temperatures and evapotranspiration rates of plants in the bag. Conclusions of immediate practical value were published in an earlier report (Kauppi & Hari, 1980).

2.2. Bag properties and plant vigor

In choosing the bag type for plant transportation, there are a number of properties that must be considered. Not only must the bag be easy to handle, it must also tolerate moisture, rainfall and varied temperature conditions. These properties are easy to determine during use of the bags in the field. Therefore, the trial-and-error principle is efficient in detecting such characteristics. It is more difficult to determine the properties of a bag which directly or indirectly affect the vigor of the nursery stock. The vigor, as discussed above, is not directly visible. It only mainifests itself well after the stock has been planted.

It has been demosntrated that the bag wall can substantially modify temperature conditions inside the bag (Leikola, 1973). This is due to cutting off the turbulent airflow in the internal bag space. It is also due to the specific bag properties which determine what fraction of the solar radiation is reflected from the bag, what fraction is absorbed by the bag wall, and what fraction is transmitted into the bag. When the bag is placed in a shaded environment, the internal temperature follows the ambient temperature, regardless of the bag material. Only the time constant involved will vary from bag to bag. But this is not the case when a bag is exposed to sunshine.

Five different bag types were compared in this study. One of them was substantially more transparent to solar radiation than the others. A hypothesis was created that this difference affects the microclimate in the bag and, subsequently, the future performance of the plants stored in it before planting. Since plants can absorb more radiation energy than the transparent bag wall, it is obvious that the temperature of plants inside a sunlit bag would be higher than that of the bag wall. Water would also evaporate from the sunlit plants and condense on the bag wall whenever the temperature of the wall was below the dew point. (This could be the case rather often if, in fact, a temperature gradient existed between the plants and the wall.) The water then would run down to the bottom of the bag, which would be cool and not capable of recycling the water back into the air. This hypothesis is illustrated in more detail with the following calculation, the purpose of which is to obtain a rough estimate of the amount of water leaving the plants.

A typical daily integral for the solar radiation energy on a horizontal surface in Finland in June is 25 MJ·m^{-2}, corresponding to an average irradiance of about 300 W·m^{-2} (Budyko, 1960). Assuming that half of the solar energy is transmitted through the bag wall, and that the plants occupy an area of 30×30 cm, the amount entering the plants would be $25\cdot(0.3\cdot0.3)\cdot0.5$ MJ, which is 1.1 MJ. The latent heat of vaporization of water at the realistic temperature of 40 °C is 2.4 MJ·kg^{-1} (Gates 1980, p. 308). This implies that there would be enough energy inside the bag to vaporize more than 400 grams of water in one day. Given the weight of the plants (10 to 25 kg) such an amount of vaporized water might be significant, particularly since the water reduction would not be evenly distributed between the plants but it would only involve the topmost plants. Four hundred grams is the total water content of 50–100 barerooted 2+1 Scots pine transplants (c.f. Parviainen, 1980).

It was hypothesized that the transparency of the transportation bag would have a significant impact on the environment inside the bag and, subsequently, on the performance of plants stored in the bag in sunny conditions. Moreover, the factors would vary rapidly in time especially during a period of time with intermittent irradiance. These hypotheses were tested with the experiments reported below.

2.3. Experiments with different bag types

General Design of Experiments. The experiments described in this section consist of i) characterization of the materials of which the five types of bags were made; ii) recording of the bags' internal microclimate under severe but realistic field conditions; and iii) assessment of the performance of plants stored inside the bags prior to planting in the field. All the field experiments were done during the period of May through September, 1978, in the Hyytilä Forest Station of the University of Helsinki (Latitude: 61°50', Longitude: 24°15').

The bag types used in the experiment were the following:

[A] *Bag A* was a white polythene bag, size 50×90 cm, with a 0.1 mm-thick wall. This bag was generally used in Finland in the 1970's for transportation of nursery stock, though use has been discontinued as discussed in detail below. The bag was produced in Finland by Amerplast Company.

[B] *Bag B* was made of double-walled polythene. The white exterior wall had been clamped to the inner black wall in a process which left no air space between the two walls. The bag size was 60×90 cm and the wall thickness (white+black) was 0.1 mm. The bag was produced by Amerplast Company in accordance with specifications required by this study.

[C] *Bag C* was a black polythene bag, size 50×100 cm, with a wall thickness of 0.05 mm. This bag, which is generally used for waste disposal, was also a product of Amerplast Company.

[D] *Bag D* was a double-walled polythene bag similar to Bag B. The inner wall of this bag was also black, but the exterior wall was a metallic silver grey. No air space was left between its walls. The bag was 60×100 cm in size and its total wall thickness was 0.1 mm. The bag was supplied by the Austrian company K. Hirsch and in German is known as the "Pflanzfrisch Transportsack" ("Fresh Plant Transportation Bag"). It has been specifically designed for storing and transporting nursery stock (Lang, 1973).

[E] *Bag E,* unlike the four other bag types, was made of paper. Its walls consisted of three layers of paper, which were not clamped tightly together, allowing two air spaces between the layers. The inner layer was covered with a thin polythene reinforcement. The bag was 40×80 cm in size with a total wall thickness of about 0.5 mm. This bag has been produced particularly for the needs of nursery stock transport by the Paperituote Company in Finland, but it has not been as widely used as Bag A.

Properties of Bag Materials. The wall materials of the five bags were studied in detail by taking measurements of short wave radiation transmittance, short wave radiation reflectance, spectral distribution of the reflected short wave radiation, and spectral distribution of transmitted thermal radiation.

The transparency of the bags to solar energy was studied in full sunlight conditions using Lambda LI-185 equipment with a pyranometer sensor. The sensor was directed towards the sun, and then covered by the bag wall. The calculation of transmittance was obtained by then dividing this reading by a subsequent reading taken from an uncovered sensor. Reflectance of short wave radiation from the different bag walls was measured with an integrating sphere (Figure 2.1.). All measurements with this instrument were conducted by the Technical Research Centre of Finland. As is standard in reflectance studies, the integrating sphere was used to generate a uniform angular distribution of irradiance onto the object surface. The radiance spectrum corresponded to CIE standard illumination A (color temperature 2856 K). The sensor was a celen cell.

The spectral properties of reflected radiation were described using a spectroradiometer system also constructed by the Technical Research Centre (Jaakkola & Saukkola, 1980). The point-source radiation installed for this particular measurement application met the bag wall at a 30 ° angle, and the reflected radiation was measured perpendicular to the wall object. Reflectance at different wave lengths was measured at five-nanometer intervals for the range 395–995 nm. The readings were expressed on a relative scale where the reflectance at 660 nm, separately for each wall material, was fixed at the value 1.0. The measurements were performed to quantify the "bag color".

The spectral properties of transmitted radiation for the longwave range 5–20 μm were measured for the different bag materials using a Perkin-Elmer 621 infrared spectrophotometer. The wave length range was selected so as to correspond to the radiation emitted from objects at 35–40 °C (approx. 310 K), which is the temperature of transplants in bags under severe field conditions (Leikola, 1973).

Recording the Internal Environment. Temperature and potential evaporation inside the bags were monitored under field conditions. One bag of each of the five types was placed on an open roof, 1.5×3.5 meters, at a height of 2.8 meters above the ground surface (Figure 2.2.). This location was selected because it was similar to an open field with respect to solar irradiance, and because it was near the field laboratory with the monitoring equipment (for description see Hari et al. 1979). Each bag was filled with 150 barerooted 2+1 transplants (Appendix 1). The bags, which were tightly closed, were lying on heat-insulating polystyrene plates fixed to the roof.

Temperature was measured with eight thermocouples placed in the internal bag spaces and connected through a data logging system to a PDP 11 computer (Lappi & Smolander, 1981). The time interval between measurements from a given thermocouple was 100 seconds. A shade was constructed for the thermocouple located in Bag A, since this bag was partially trasparent. The thermocouples remained in the bags for 42 days, from May 11 to June 23, 1978.

Conditions for evapotranspiration were measured inside the same bags from June 14 to 23, 1978. This was done using equipment described by Hari et al. (1975), but modified for this experiment. The method is based on the assumption that measuring the output from an unventilated pair of dry and wet thermocouples can yield a rough estimate of the conditions for evapotranspiration. In this modification the sensitivity of the equipment was improved by connecting five adjacent pairs of thermocouples in series.

All measurements were taken while the thermocouple sets were positioned within the bags at a height of approximately three centimeters above the topmost transplants in the bag. A shade was constructed for the equipment set located inside the partially transparent Bag A. Two sets of sensors were used alternatively in such a way that, after an average period of one day, one of the sets was moved into a new bag, thus gaining measurements sequentially from all the bags. All five bags were weighed at 2.00 P.M. on June 14, and again at the same time on June 21.

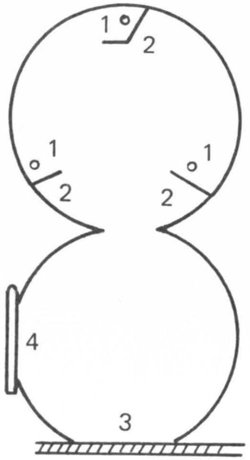

Figure 2.1. Integrating sphere used in the reflectance measurements: 1=radiation source; 2=shade against direct radiation; 3=study object; 4=sensor.

The thermocouple sets provide data on the difference of dry and wet temperatures. For studying the response of plants to the environment it would be very useful to convert this data, even if only roughly, to measurements of the evaporation rate. Such a conversion was done by calibrating the device with the evaporation measurements provided by weighing small open dishes filled with water (Vaartaja 1954, Hari et al. 1975). Measurements for the calibration were taken in outdoor conditions, though sheltered from direct solar radiation and rainfall.

The evaporation measurement obtained from the dishes was first converted to the average declining rate (mm/h) of the water surface for the four dishes over the time period between two subsequent weighings. This figure was then related to the time integral of the output from the thermocouple sets over the same time period. The ratio between the two readings was obtained. Evaporation coefficients characteristic of each of the two thermocouple sets were calculated as an average of eight ratios gained from such measurements, each of which represented different environmental conditions. This calibration made it possible to express the output from the thermocouple sets, not only in terms of the difference between wet and dry temperatures, but also in terms of potentiel evaporation rate, mm·h^{-1}.

Figure 2.2. Recording the bags' internal microclimate: Bag types from left to right: C, A, B, E, and D (*left*); Instruments inside Bag A: wet and dry thermocouples, and the Lambda LI pyranometer sensor. The pyranometer, which normally was used in the ambient space, is here installed inside the bag (*right*).

Planting Experiment. Storage treatment for test transplants (herein called Experiment A) took place simultaneously with the temperature measurements. Forty fresh Scots pine transplants (Appendix 1) were added to each bag on June 14. Twenty of these test plants was placed horizontally underneath the 150 original transplants, while the other group of twenty transplants were placed horizontally on top of the the original transplants.

After one week of exposure to field conditions the test transplants were planted in an open nursery field in four blocks, each block containing five transplants from each of the ten different treatment modes (five bag types; top and bottom placement). The possible damage of the plants was described 12 weeks after planting, at which time shoot and needle growth for that season had already ceased. Transplants then were graded into four vigor classes. Dead transplants, that is, transplants with no obvious living buds or needles, were grouped into Class 0, and the remaining three classes were reserved for living transplants with increasing vigor from Class 1 to Class 3 (Räsänen et al. 1970).

Another similar experiment (Experiment B) utilized four bags, all of which were type A (white polythene). In other respects, the experimental design was the same as that described in the two preceding paragraphs, including a one-week exposure to severe field conditions, and the addition of 40 test trasplants placed on top and underneath the original stock. The bags of Experiment B were placed on the ground surface in an open field about 50 meters away from the bags of Experiment A. Transplantation and inventory procedures were identical to those of Experiment A.

2.4. Results of bag comparisons

Wall Characteristics. The wall materials differed clearly from bag to bag with respect to transparency, reflectance and absorbance (Table 2.1.). Bag A (white polythene) transmitted about 50 per cent of the incident solar radiation and absorbed virtually no radiation. Bag B (double wall polythene) had the highest reflectance figure and the second lowest absorbance figure. This bag transmitted 3 per cent of the incoming solar radiation. Bag C (black polyhene) absorbed about 90 per cent of the incoming radiation. A high degree of absorbance also characterized Bag D ("Pflanzfrisch Sack)". With Bag E (triple-wall, paper) roughly half of the radiation was reflected and the other half was absorbed.

Bag B was the most bluish in color while efficiently reflecting the radiation within the range 400–500 nm (Figure 2.3.). Since a quantum with a short wave length has a high energy content (see Nobel 1970, p. 165), and since the radiation energy maximum is in the range of 400–500 nm (Figure 2.3.), the bluish color of Bag B contributes to the superior reflectance of this bag. Ideally, of course, a bag should reflect all radiation within the range 300–2000 nm; but since this is impossible in practice, the bluish color provides at least a slight advantage. Bag E (triple-wall, paper) in contrast to Bag B (double-wall,

Table 2.1. Transparency, reflectance, and absorbance of the bag materials for solar radiation. Transparency and reflectance figures are based on measurements which are then used for calculating the absorbance. Figures are also indicated in parentheses for a single paper layer of Bag E.

Bag type	Relative proportion, % Transparency (T)	Reflectance (R)	Absorbance (100 - T - R)
A=white	50 [±10]	62 [±10]	-
B=white/black	3.0	67	30
C=black	0.1	9.5	90
D=silver/black	0.01	28	72
E=paper	2.0 (27)	47 (47)	51 (26)

polythene), had a relatively low total reflectance, partially due to the fact that its reflectance spectrum did not coincide with the solar irradiance spectrum (Figure 2.3.).

The bags also differed from one to another with respect to transparency to long wave heat radiation (Figure 2.4.). Bag A and Bag C had fairly similar spectra, with a transparency ranging between 40 and 70 per cent, excluding three peaks with low transparency. Similar peaks also characterized Bag B, which had a lower overall transparency (30–40 per cent) within the wave length range of 5–13 microns, but the highest transparency of all five bags of the wave length range 13–20 microns. The "Pflanzfrisch Sack" and the paper bag did not transmit much radiation; for most of the inspected spectrum the transmittance of these bags was lower than 10 per cent.

Bag Internal Environment. The daily course of temperature inside the bags appeared to show some consistent characteristics (Figure 2.5). At night, the bag internal temperature converged to the ambient air temperature. In sunshine, however, the internal temperature ranged from 10 to 25 °C higher than the external temperature. At midday, when sunshine began after a cloudy period, the temperature was obseved to increase at a rate of approximately 2 °C per minute, reaching a steady state in 10 to 20 minutes. A decrease of a similar rate occurred after the beginning of a new cloudy period.

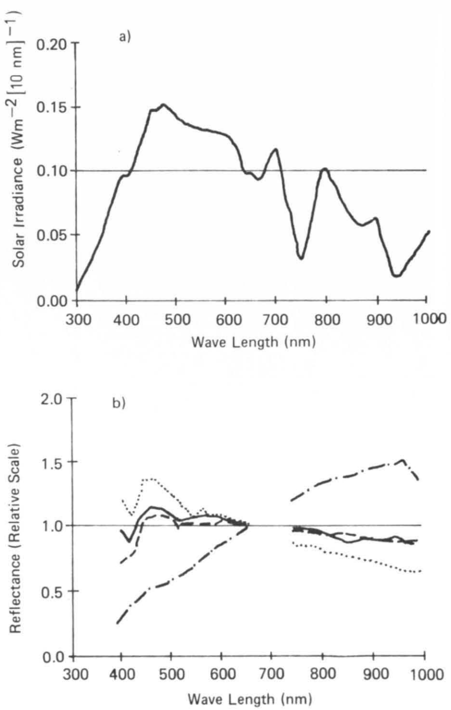

Figure 2.3. Solar irradiation spectrum, see Valley (1965) (*a*), and relative reflectance of four of the bags: (——) Bag A; (· · · · ·) Bag B; (- - - -) Bag C; and (- · - · -) Bag E (*b*).

The highest instantaneous temperature was observed in white Bag A: for a time period of about 2 minutes the temperature reached 50 °C. Temporal variation within the bags was substantially larger than that in the ambient air (Figure 2.5.). The enhancement of the temperature variation was due to the variations in the solar radiation. The potential evaporation rate inside the bags also appeared to follow the course of the incident solar radiation. In some cases the potential evaporation rate doubled or even tripled within five minutes (Figure 2.6.). The weight loss of the bags (Table 2.2.) was so small as to suggest that potential water flow through the bag walls did not have significant drying effects in any of the five bags.

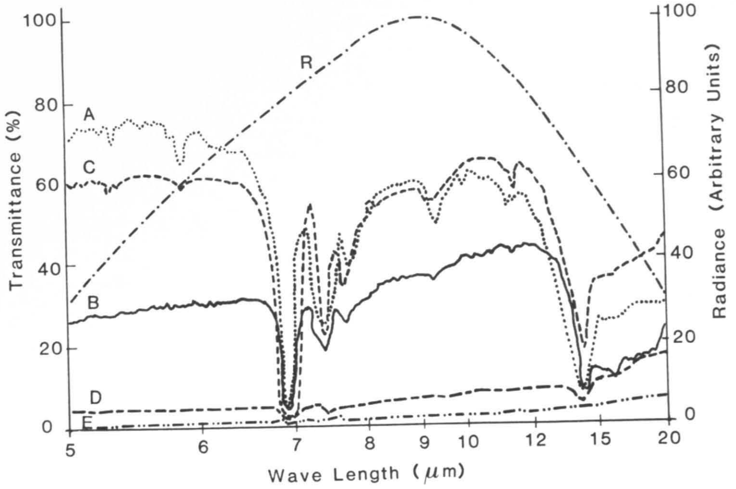

Figure 2.4. Radiation emission from a black body at 310 K (*R*) according to Valley (1965), and the transmittance characteristics of Bag A; Bag B; Bag C; Bag D and Bag E.

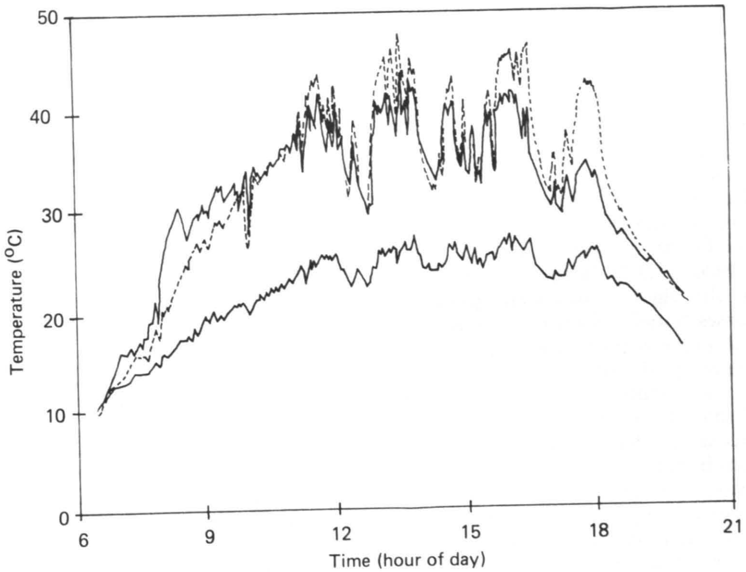

Figure 2.5. Ambient air temperature (——), and bag internal temperature for white Bag A (- - -), and for black Bag C (——), May 18, 1978.

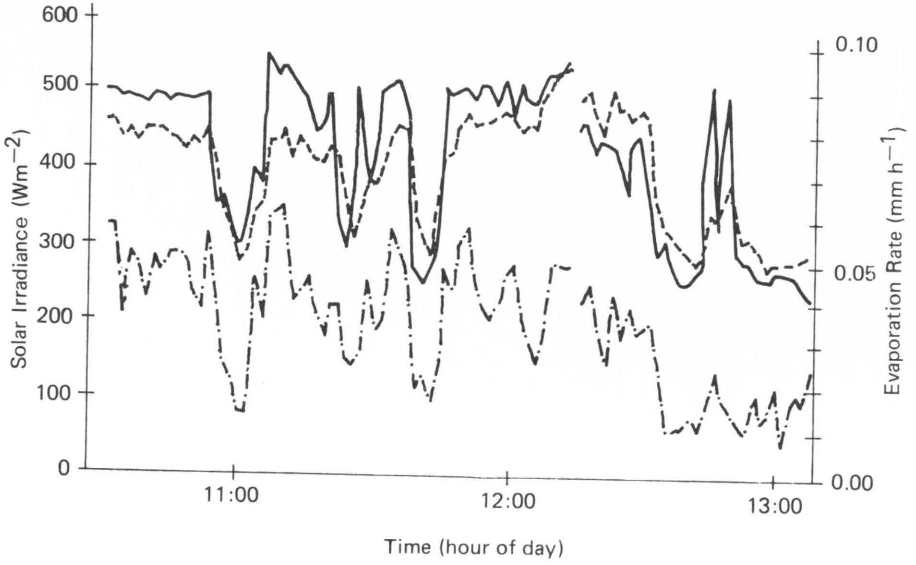

Figure 2.6. Ambient solar irradiance (——) during midday hours June 10, 1978, and the evaporation rate measured with the wet and dry thermocouple equipment inside Bag A (- - -) and Bag C (- · -).

Transplant Performance. Most transplants, except those in white Bag A, survived the one-week storage treatment in relatively good shape, and were classified 12 weeks after planting into either of two classes: 2 (good) or 3 (very good) (see Figure 2.7; from Experiment A). Transplants located on top of the pile inside the white Bag A, however, appeared to suffer from the treatment. The effect of the treatment was tested statistically using the Fischer-Irwin test (see Vasama and Vartia 1980, p. 562), in the following way.

First, the vigor classes were grouped so that classes 0 and 1 formed one group, and classes 2 and 3 formed another group. Then the frequency distribution of the treated transplants (white bag/top) was tested against that of the control plants. A similar comparison was done separately for the distributions from each of the different bags (top and below). The probability of the distribution white bag/top being different from the control distribution was 0.9994. None of the other distributions showed a statistically significant difference, with a probability higher than 0.2, from the distribution of the control transplants. A deterioration of the transplants stored on top of the pile in white Bag A was also observed in Experiment B (Figure 2.8.).

Table 2.2. Weight of the bags before and after one week of exposure.

Bag type	Date June 14 Weight, kg	June 21 Weight, kg
A=white	8.50	8.50
B=white/black	7.80	7.80
C=black	6.90	6.85
D=silver/black	6.85	6.80
E=paper	6.45	6.40

2.5. Conlusions drawn from the comparison

Substantial temporal variation was observed in the indicator variables of the plant environment. The temperature varied more strongly inside the bag compared to the variation outside of the bag. The highest temperature (>+50°C) as well as the highest potential evaporation (approx. 0.3 mm/h) were found inside the partially transparent Bag A. This was the case although the bag, as compared to other bag types, was characterized by several properties which would serve to maintain low temperatures and evapotranspiraton rates. Bag A had a fairly high reflectance, it was rather bluish in color, and it transmitted a large share of thermal long wave radiation. These counteracting properties obviously could not compensate for the effect of transparency in increasing temperatures and evapotranspiration rates. The transplants which had been stored in Bag A were less vigorous than those from other bags. These results indicate that a high transparency of short wave radiation, such as occured within Bag A, will, in certain field conditions, generate particularly severe conditions inside the bag.

Some reservations regarding this comparison have to be mentioned. Measurements of radiation balances in characterizing the bag wall were relatively inaccurate (Table 2.1.). In practice, the number of plants located inside the bags is greater by a factor of two to three, than that used in the experiments of this study. The unventilated psychrometer used for measuring the evaporation rate has

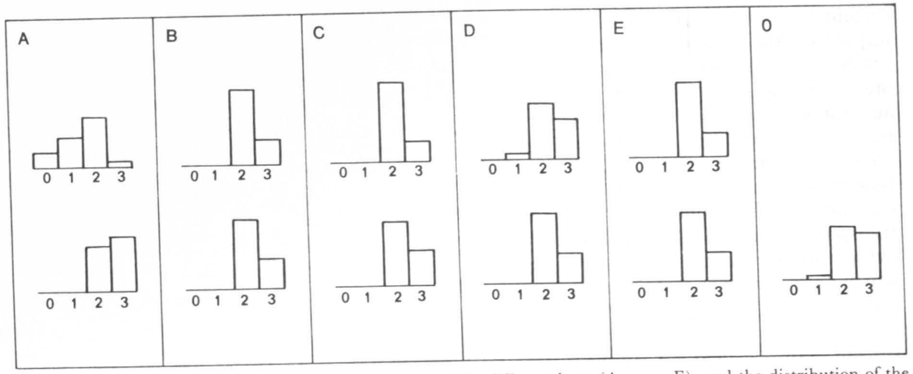

Figure 2.7. Vigor class distributions of transplants stored in different bags (A , . . . , E), and the distribution of the control transplants (0). The above distributions stand for the lots stored on top of the pile, and those below for the lots stored at the bottom of the bag. Vigor increases in this classification from 0 (dead plants) to 3 (very good plants).

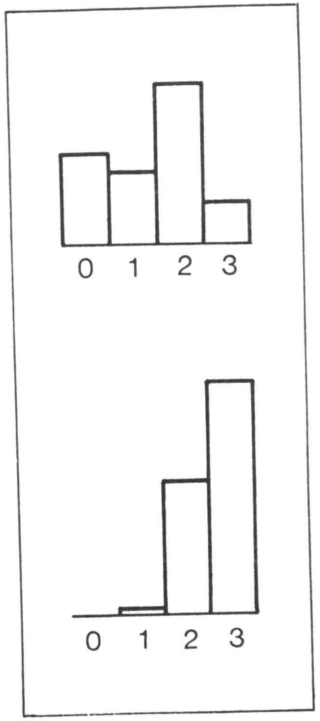

Figure 2.8. Vigor class distributions (top and below) from plants of Experiment B.

certain restrictions. All the factors have an impact on the reliability of the quantitative results. Fulthermore, one may argue that the one-week exposure to sunny conditions exaggerates potential mistreatment. Nevertheless, as also indicated by the plant performance measurements, the partially transparent Bag A tends to contain different and more extreme weather conditions than the non-transparent bags. Such a difference, even if overemphasized in this experiment design, is worth noting in large scale reforestation programs. Of all the bags studied, the partially transparent Bag A would be least suitable for storing plants in field conditions.[1]

Recognition of the relevant temporal scales of phenomena has been introduced as a fruitful starting point for ecological and ecophysiological analyses (Osmond et al. 1980; Hari, 1980; Clark et al. 1983). It was found in this comparison that the temporal variations are even more substantial within the transportation environment than they are in the free atmosphere. In the following Section 3, concepts and methods are developed which cope with the microscopic nature of the variation, and which assist in analysing the consequences of such a variation on plant vigor.

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[1] The foresters in charge of executive planting programs in Finland responded immediately to these study results. After being informed in October 1978 of the results of this study, the representatives of both public and private forest nurseries decided to withdraw the partially transparent Bag A from the market. This decision was put into practice for the 1979 season (Kauppi, 1979). Type A bags were then replaced by Type B, which had been developed and used for the first time in this study. The additional annual expense for the forest nurseries, genereated by the new, 20 per cent more expensive bags was a total of 40 000 Fmk (in 1979 currency, equivalent to about 60 000 French francs). This investment was considered moderate, since the sum is no greater than approximately 0.02 per cent of the total costs used in Finland for forest tree planting.

3. RESPONSE OF THE PLANT: THE DYNAMIC INJURY MODEL

3.1. Stress duration and quantitative stress level

Two views have prevailed in the literature on the development of damage in tree transplants. The first is that the amount of damage observed in the transplants has been related to the duration of the exposure in which the damage was induced. In this case the plants' environment within the exposure period has been fixed or assumed constant. There is empirical evidence that stress duration, indeed, has a key role in injury development (Jakabffy, 1975). In the second view, the damage has been studied as a function of some quantitative variable characteristic of the plants' environment within the exposure period. In this case the duration of the critical period, in turn, has been fixed constant. Långström (1971), for example, has demonstrated the impact of environmental factors on injury development. Both of these approaches provide data in which the obseved 'response', damage, is expressed as a function of a 'dose', either the stress duration or the level of the stress. Elaborated statistical methods are available for analyzing such data sets which are frequently called bioassays (Finney, 1971).

The statistical methods are directly applicable to conditions where the response variable is connected to the dose variable in a fairly direct causal way. The methods are valid especially when both the dose and the response can be considered to take place instantaneously without essential time dimensions or delays. Such requirements are often met, for example, in medical research when a dose of medicine is given to each subpopulation in different levels. The research problem can be considered *static* in cases when either the stress duration or the level of the stress is fixed. Analysis of such data can be done using the bioassay methods which are easily available in statistical computer packages such as the BMDP (BMDP . . ., 1979).

The statistical methods, in their basic form, are less powerful in cases where the response accumulates slowly and when it is driven by a "dose" which has a long duration and varying levels within this period. Such a dose has perhaps only an indirect causal relationship to the response of interest. This is typically the case with the injury development in tree transplants as was indicated in the preceding Section 2. The plants seldom experience sudden dosages of unfavorable conditions but more often such conditions prevail over a period of time, their level being sometimes weaker and sometimes stronger. Temporal variations are microscopic. Decrease in survival and growth occurs only after an long period of time when the unfavourable conditions perhaps have already disappeared. Hence, the process is essentially *dynamic* in character.

In appears that there are no established methods available for analysis of empirical data of dynamic dose-response relationships. Considering tree transplant studies, new methods need to be developed. *Such new methods would not substitute the statistical dose-response methods but they would rather expand the applicability of the statistical methods to a dynamic context.* In Section 3, a theoretical model is developed for describing dose-response relationships for dynamic and indirect processes. For this purpose, the concept of injury is defined based on silvicultural considerations. The concepts of strain, stress, and stress resistance are then described as used in botany by Levitt (1972). Two different concepts are defined to characterize the strain. One is a state variable and can be related to injury. The other is a rate variable and can be related to stress and stress resistance. A dynamic model is introduced for describing the mutual relationships of these concepts. At the end of Section 3 applications of the model in designing experiments are discussed.

3.2. Injury, strain, stress and stress resistance

The main goal of the tree planting programs in Finland, and in many other regions of the world, is to obtain sufficiently dense and fast growing young stands. In relation to this goal, **injury** to individual plants can be defined in two ways: tree death or slow tree growth. 'Slow' tree growth is discussed in detail below. This injury definition is used in this study for evaluating the importance of the factors involved in the process preceding the injury.

Levitt (1972) has introduced the concept of **strain** to describe the physiological pathway which precedes the injury. Before tree death or decreased tree growth, obviously several processes occur which gradually decrease plant vigor, but which are not directly visible before the manifestation of the injury. All the plant properties which in qualitative or quantitative terms differ from the respective propertis of a vigorous tree are grouped together under the concept of strain.

Stress has been defined as an *environmental* factor capable of inducing a potentially injurious strain on an organism (Levitt, 1972). Stress suffered by tree transplants would include factors such as high temperature, high potential evaporation, radiation of any kind, toxic chemical compounds, etc. Pests and pathogens are also included in the stress factors as they belong to the environment rather than to the plant itself. Stress is in this study perceived only to include factors acting before planting.

The development of strain is not only due to environmental stress factors; plant *internal* factors are always involved. The plant factors affecting the process of injury, have been grouped together under the term **stress resistance** (Levitt, 1972). This concept is neccessary because a given environmental stress yields different strains (and injuries) for different plants. Even the same plant reacts to a given environment in various ways depending on the phenology, nutrient status and other factors. An example of a measure for stress resistance is the root regeneration potential (RRP) as introduced by Stone et al. (1962), and further developed by, for example, Burdett (1979). Other factors included in the concept 'stress resistance' would be root to shoot ratio (e.g. Huuri et al. 1970), nitrogen content of the tissues (Glatzel. 1973), shoot water potential (Havranek, 1975), frost resistance (Sakai, 1960), etc.

In general, stress resistance properties fall into either of the two clearly different categories: genotypic characteristics and phenotypic characteristics. Stress resistance factors are genotypically fixed to vary within a certain range, but within this range there is phenotypic variability due to environmental growing conditions.

An additional concept, **site environment,** is used in this study to denote environmental factors present at the planting site, which affect the functioning of the tree.

It is important to notice that the stress terminology is bound to the perceptions of the investigator. Timmis (1980) points out the difficulties in trying to define stress in a strictly biological way. It is the *normal* case that plants grow in suboptimal conditions, *i.e.* under stress, and plants "are designed by nature to grow that way". Indeed, it has been shown that plant growth can be substantially accelerated from the traditional levels (Wood & Hanover, 1981;Farnum et al. 1983), although this doesn't imply that using fast growing transplants would directly improve reforestation results (Ingestad, 1978). Considering Timmis's viewpoint it seems obvious that *stress, rather than being an invariant property of either the environment or the plant-environment-system, is to be defined bearing in mind the particular purpose for which the plant is grown.* The injury as well as the stress factors affecting it are thus seen from the viewpoint of the "predator", man (see Lindqvist, 1977).

The same thing has been taken into account by, for example, Glerum and Mullin (1976) who define planting stock quality to be high when "the stock is produced at the lowest cost and when it starts to grow, weather permitting, as soon as it has been planted out and keeps growing vigorously until the end of its rotation period" (see also Schmidt-Vogt 1966, p. 128). The definition, while including the cost considerations, indicates that it is not feasible to describe planting stock quality using biological concepts alone. In this study the perceptions of the investigator were made explicit by defining the plant injury concepts as threats to the goal of obtaining dense, fast growing young stands.

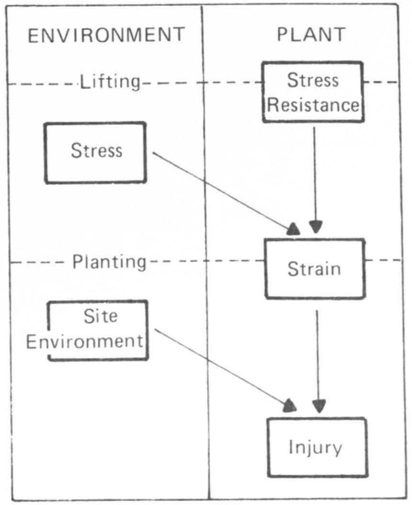

Figure 3.1. Mutual relationships of the terms used for analysing the development of plant injury.

Figure 3.1. summarizes the relationships of the concepts: Strain results from stress and stress resistance, and injury results from strain and site environment.

3.3. Dynamics of the injurious process

Let us assume that there are quantitative variables to measure injury, strain, site environment, stress, and stress resistance. The numerical values of such variables would obviously vary with the time of observation. Stress variables – frost, high temperature, radiation, etc. – tend to vary rather fast over time. Injury variables represent the other extreme: reactions of survival and growth are slow. Different time patterns pose one challenge to the analysis. By the time the injury appears there may be no signs left of the stress which induced it. This problem was described above in connection with the bag environments.

In order to analyse the dynamic characteristics of injury development one must describe the *time patterns* of the factors involved. This is to be done using variables which, in principle, are defined at any given instant. In practice, the variation need not neccessarily be monitored continuously; repeated sampling offers a more convenient technique. Irrespective of the measurement technique, however, the time pattern (time = t) of the stress, s.

$$s = s(t), \qquad (3.1.)$$

as well as the time pattern of the stress resistance, r,

$$r = r(t) \qquad (3.2.)$$

must be described.

With these descriptions it then becomes possible to describe the time pattern of the strain, u:

$$u = u(s(t), r(t)). \qquad (3.3.)$$

These time patterns are essentially based on observations referring to the values of the variables at every time instant. It should be made possible, however, to view injury development as a cumulative process. Therefore, it is important to introduce the time integral for the strain, defined in this study as **accumulated strain**, U:

$$U = \int_{t_0}^{t_1} u(s(t),r(t))dt. \qquad (3.4.)$$

In order to specify the difference between the two strain concepts, the term **strain rate** is adopted for the instantaneous strain, u.

Now, using Equation 3.4. and selecting an appropriate time interval from t_0 to t_1, it becomes possible to take into account the stress factor, the stress resistance factor, and the "time factor" in deriving a quantitative figure for the concept of accumulated strain. This figure can then be related to the injury, I:

$$I = I(U) \qquad (3.5.)$$

The main additional feature of this formulation, compared to Levitt's (1972) original concept, lies in the two forms of strain. Accumulated strain is a state variable which can be related to the injury (Eq. 3.5.). Strain rate is a rate variable and can be related to stress and stress resistance (Eq. 3.3.). Equation 3.4. defines the relationship between the two strain concepts and thus bridges the gap between the fast and the slow variables. These formulations, Eqs. 3.1.-3.5., are used as the conceptual framework of this study, and are called the Dynamic Injury Model.

For simplicity the Dynamic Injury Model is applied explicitly only up to the moment of time when the tree is planted. Yet, at least in theory, injury is not completely determined by the factors before planting. Heinze & Fiedler (1978) have demonstrated positive effects due to shading on trees suffering from a water deficit. Glatzel (1973) reports interactions between plant water uptake and fertilizer application at planting. On the planting environment there are many environmental factors which could be viewed as stress. Together with plant internal factors they would induce a strain in the plant. Such a process is exactly what the Dynamic Injury Model describes. However, a simplified static model is used to account for the potential modifying effect of site environment on injury development. This is done by analysing plant injury as a function of the site environment, E, and of the accumulated strain at planting, U_{fix}:

$$I = I(U_{fix},E). \qquad (3.6.)$$

This view replaces Eq. 3.5. whenever variation in site factors is expected to influence the process of injury.

Experiments guided by the Dynamic Injury Model are reported in Section 4. In some cases the trees are planted in the stardardized conditions of an open nursery field. Then the injury is related directly to the accumulated strain (Eq. 3.5.). In other cases, there is variability in the planting environment. Then the injury is related both to the accumulated strain by planting and to the site environment (Eq. 3.6.).

Hari (1980) describes a method which deals with the temporal and spatial variation of the environment by way of analogy. The description applies to the Dynamic Injury Model, thus indicating the way in which the spatial variation of the environment may also be taken into account. However, the emphasis of this study is placed on dealing with the temporal variation.

Using the Dynamic Injury Model it is possible to combine the impact of stress duration and that of the quantitative level of the stress into a uniform approach. Moreover, it is possible to use stress resistance as a variable in the analysis without the need to fix it to specific cases. It is worth noting that the description covers the static dose-response approach as a special case where stress, stress resistance, and strain do not vary with time, and where injury is without an essential delay induced by a stress of fixed duration. The Dynamic Injury Model, however, is not restricted to this special case.

3.4. From the conceptual to the experimental

Of the two injury variables introduced – tree death and slow tree growth – the former is easily ascertained, but it is more difficult to assess how much growth, in fact, should be considered too small. Growth expectations are not similar in different climates, on different sites, and for different tree genotypes. Also, as discussed above, the expectations depend on the perception of the investigator. Having improved the level of succes, for example, the old standards are no longer satisfactory. Such varying factors are difficult for the analyst as the reference point will never be universal. One way to deal with these difficulties is to use reference plants in order to determine the most relevant growth expectations. This procedure is used in this study. Reference transplants from standard nursery stock are treated carefully in all phases of storage, transportation and planting, but are not given any more attention than in usual in properly executed planting. With these transplants as comparisons, slow tree growth observed in stressed transplants can be quantified and thus used as a measure of plant injury.

It was assumed in the preceding Section 3.3, that there exist variables with which one can describe quantitatively the time patterns of stress and stress resistance. However, the introduced concepts such as stress, strain and those in Eqs. 3.1.–3.6. are still rather highly aggregated. Therefore, in order to reduce the aggregated concepts into a more concrete form, the concepts must be simplified.

For the purpose of disaggregation it is useful to view the concepts stress, stress resistance and strain as vectors with a large number of components. This approach solves an obvious feasibility problem of the model: All the components are measurable. But the vector representation also creates a new feasibility problem: With rich imagination, and also supported by experimental evidence, it will be easy to define vector descriptions with a very great number of potential components. No experimental program can evaluate all the potential relationships (Casti, 1982).

Instead of an effort to describe all the potential factors – all vector components – a series of experiments was designed in order to focus on a limited number of relationships. The Dynamic Injury Model was used as a guide for questions such as:

- What are the relevant injury variables?
- Which theories would describe the physiological pathway preceding the injury?
- What are the relevant stress variables?
- What is the relevant range of variation of the stress variable?
- What is the time step for describing the stress variable?
- What would be relevant stress resistance variables? Range? Time step?
- How can strain rate be related to stress and stress resistance; for example, could a multiplicative model be suggested?
- What would be relevant variables for strain rate; are there measurable strain variables, or could one use computational estimates as was done by Pelkonen (1981) when analysing the gradual recovery of tree photosynthesis in the spring season?
- Any recovery (negative strain rate)?
- What would be relevant time periods for integrating the accumulated strain?
- Would it be neccessary to substitute the simple integration described in Eq. 3.4 by a procedure which emphasizes recent events over the early history of the process?
- What is the relative importance of one stress factor over another?

Additional questions emerging from Eq. 3.6. are:

- How best can injury be related to strain and site environment?
- What would be the relative importance of the accumulated strain at planting and the site environment in generating the injury in actual field conditions?

Some of these questions are addressed in the empirical part of the study as is described in Section 4. The intention was not to exploit all the possibilities that the Dynamic Injury Model would provide. However, the empirical part of the study was not conducted only to demonstrate the properties of the Dynamic Injury Model. Experiments were also designed to address issues of practical interest.

Before entering into Section 4 which discusses empirical results, the materials and methods used are briefly described. Specifications of dependent variables (injury variables) and independent variables (strain variables) are given, and methods are clarified for relating the former to the latter.

3.5. Material and methods

3.5.1. Dependent variables: injury

Survival

The data of this study consisted of *sublots* of Scots pine transplants which were subjected to a range of stress treatments before planting out in the field. A sublot in this study consisted in most cases of 20 transplants. The sublot was viewed as a sample of a real forest regeneration stock; it was the experimental unit from which the injury variables were measured.

Growth and survival were measured typically after 17 months. Plant **survival** was measured from the sublot as the share of plants with living buds or needles. In normal cases the resolution was 5 per cent units (1/20). The symbol I_s (**I**njury in terms of **s**urvival) was used to denote survival. A relative scale was used from 1.0 (100 per cent survival) to 0.0 (no survival).

Growth

The other injury variable, slow growth, was assessed also from the sublot. Growth was measured as the height of the leader shoot formed during the second growing period after planting. Reference plants were needed to view the observed growth of the sublot against a relevant background level. The average height of the leader shoots was determined for the treated sublot and for the reference sublot, and the ratio was formed between the two figures: treated/reference. This ratio is called the **Growth Index** and is abbreviated as I_g (Injury in terms of **g**rowth). The Growth Index is obviously bound between 1.0 and 0.0. However, figures lower than 0.2 are rare, since, if treated plants survive they seldom produce zero growth.

Productivity

A third, less important injury variable was calculated from the survival and growth data. Survival and growth, when treated separately as done above, describe the morphological character of the plant response. These variables, however, produce ambiguous results for one who would like to understand the silvicultural implications of the injury. Suggestions have been made for combining the information of survival and growth in order to obtain an index for 'reforestation value' (Raulo, 1976; Huuri et. al 1982).

Volume growth of a young stand is the product of both the survival and of the volume growth of the average survivor. A tentative 'productivity index' is developed based on this notion.

The available data has serious constraints. It is restricted to the two first growing seasons. Much of the differentiation will occur after that phase. The spatial distribution of plants (see Pohtila, 1980) would need to be included for such indices (Huuri et al. 1982). The index developed below was, however, considered useful as it illustrates the fact that growth and survival variables, when used in isolation, tend to underestimate the silvicultural injury. Moreover, the index is developed with reference to theoretical population ecology, and this connection might provide an interesting and useful basis for developing the index further in forthcoming studies.

For calculating volume growth, i.e., for multiplying survival by growth, the survival is readily available as I_s. The Growth Index, however, can not be taken as the measure of growth because it was defined in terms of elongation. Growth would have to be expressed as the increment of either volume or mass. These desired variables are proportional to the cube of a linear dimension of the plant, for example shoot height (White & Harper, 1970; Gorham, 1979; Kauppi et al 1983). The growth component of the productivity loss was approximated from the available data by taking the cube of the Growth Index, I_g. This gave rise to the definition of the **Productivity Index**, I_p:

$$I_p = I_s(I_g)^3 \qquad (3.7.)$$

As I_s and I_g varied between 0.0 and 1.0, also I_p is bound to vary within that range.

3.5.2. Independent variables: strain

Independent variables for the analysis were introduced which can be interpreted as measures of accumulated strain and which were defined in measurable terms (Table 3.1.). Some of the factors could be defined also without the Dynamic Injury Model either as stress duration or as the quantitative level of the stress as was discussed earlier in the first paragraph of Section 3.1. Such variables were included in order to compare them with typically model-oriented variables, and also in order to seek the simplest basis for the instructions of large scale forest regeneration. The Dynamic Injury Model, however, includes these variables as special cases.

Unlike the injury variables, the strain variables were experiment-specific. Definitions and measuring techniques for the independent variables are given below at the beginning of experiment reports. Each experiment utilized several (4–9) sublots. Each sublot was subjected to a specific amount of accumulated strain. This set of sublots provided the data set for relating injury to the strain, as was desired for Eq. 3.5.

3.5.3. Relating injury to strain

Survival

The logistic function (e.g. Chatterjee & Price, 1977) was used for Eq. 3.5. when relating the strain, U, to the survival, I_s. Using two parameters, b_0 and b_1, the logistic curve is defined as

Table 3.1. Independent variables used in the experiments for quantifying the accumulated strain.

Experiment	Variable name	Symbol	Unit	Dynamic Injury Model necessary?
4.2.1	Stress duration	Δt_s	h	no
4.2.2., 4.2.3., 4.2.6., 4.2.7., 4.2.8.	Potential evapotranspiration	U_e	mm	yes
4.2.3.	Solar irradiation	U_q	MJ	yes
4.2.4.	Temperature	T	°C	no
4.2.8.	Effective temperature	U_T	Degree days	yes
4.2.5.	Vibration	U_a	m/s²	no
4.2.5.	Dropping	not defined	not defined	no

$$I_s = \frac{e^{(b_0+b_1U)}}{1+e^{(b_0+b_1U)}} \qquad (3.8.)$$

This can be expressed as

$$I_s = \frac{e^{b_1(\frac{b_0}{b_1}+U)}}{1+e^{b_1(\frac{b_0}{b_1}+U)}} \qquad (3.9.)$$

The following form is obtained by denoting $-b_1 = s_s$, and $-b_0/b_1 = s_{50}$

$$I_s = \frac{e^{s_s(U-s_{50})}}{1+e^{s_s(U-s_{50})}} \qquad (3.10.)$$

In this form the parameter s_s expresses the steepness of the curve and the parameter s_{50}, in a particularly convenient way, is the amount of accumulated strain corresponding to 50 per cent survival (Figure 3.2.). In toxicology the LD_{50}, dosage lethal to 50 per cent of the population, is often defined in a similar way. Estimation of the parameters for the logistic curve was conducted in practice by using the BMDP program PLR (BMDP . . . , 1979).

Growth Index

A one parameter function was fitted to the data in order to relate the Growth Index, I_g, to accumulated strain, U:

$$I_g = \frac{g_{50}}{g_{50}+U} \qquad (3.11.)$$

This function is convenient, since for reference plants ($U = 0.0$) the function is bound to predict no growth injury ($I_g = 1.0$). With increasing U, I_g approaches asymptotically 0.0, the slope of the curve depending on paramater g_{50} (Figure 3.3.). Moreover, the parameter g_{50} has a direct practical interpretation. It is the value for accumulated strain which cuts the Growth Index to half (U, when $I_g = 0.5$). The Growth Index was calculated for a sublot only if seven or more plants survived.

Productivity Index

Data of Productivity Index, I_p, were treated in the same way as that of the Growth Index. The same function was fitted to relate I_p to accumulated strain, U:

$$I_p = \frac{p_{50}}{p_{50}+U} \qquad (3.12.)$$

Thus the parameter p_{50} (**50** per cent **p**roductivity) indicates the amount of accumulated strain which reduces the Productivity Index to half of the reference level.

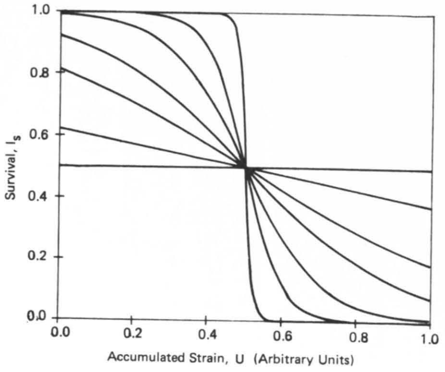

Figure 3.2. Logistic response function. The parameter s_{50} is fixed in this example to 0.5, while s_r varies from 0 (through −1, −3, −5, −10, and −20) to the value of −100 which forms the steepest line.

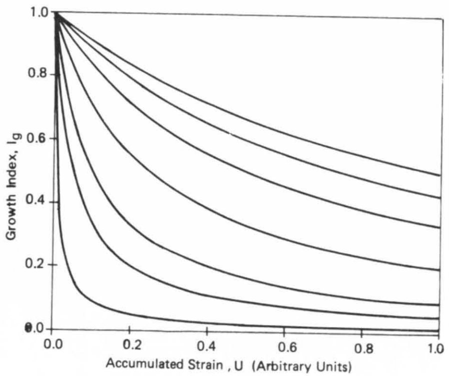

Figure 3.3. The one-parameter function used for fitting the Growth Index data. Parameter g_{50} for these curves range from 1.0 (through 0.75, 0.5, 0.25, 0.1, and 0.05) to 0.01.

4. MANIFESTATION OF THE INJURY: EXPERIMENTS FOR RANKING SELECTED FACTORS

4.1. Design of the experiments

Section 4 consists of a series of reports on experiments which aim at ranking the importance of selected factors as regards to the manifestation of the potential injury. At the beginning of each report, a hypothesis underlying each particular experiment is deduced based on the Dynamic Injury Model developed above. After that, the materials, methods and results are described, and also briefly discussed before reporting the next experiment.

The experiments reported in Sections 4.2.1.–4.2.5. are designed in order to screen the stress factors. For this reason the stress resistance factors are standardized by using similar plants for every stress treatment, and the variability of the site environment is minimized by planting the transplants side by side into a nursery field which is a relatively homogenous site with respect to microclimate and soil factors, as compared to a typical forest opening (Figure 4.1.). On account of these arrangements it is considered, within Section 4.2., that the degree of injury is governed by the strain rather than the site environment. This implies that Eq. 3.5. is used rather than Eq. 3.6. Also it is considered that strain is governed by stress rather than stress resistance. This implies that $r(t)$ of Eq. 3.3. is replaced by a constant.

Later, in Section 4.2.6, a particular stress factor, high potential evapotranspiration, is treated in greater detail. Resistance of the plant shoot to this stress factor is compared to that of the plant root. Finally, Sections 4.2.7 and 4.2.8 are devoted to studying the relative importance of site conditions in modifying the injury originally induced by the stress. In this part of the study, injury is related to the variations in both site factors and strain; Eq. 3.6. is thus applied.

4.2. Stress factors, and the impact of the planting site

4.2.1. Stress duration

For developing consistent handling instructions for large-scale forest regeneration it would be ideal if one were able to establish a universal relationship between the stress duration and the plant injury. In fact, for practical purposes, a time recommendation of two minutes has been introduced as an upper limit for exposing roots of barerooted transplants to open air. This recommendation, which is given as a rule of thumb, without a detailed reference to prevailing environmen-

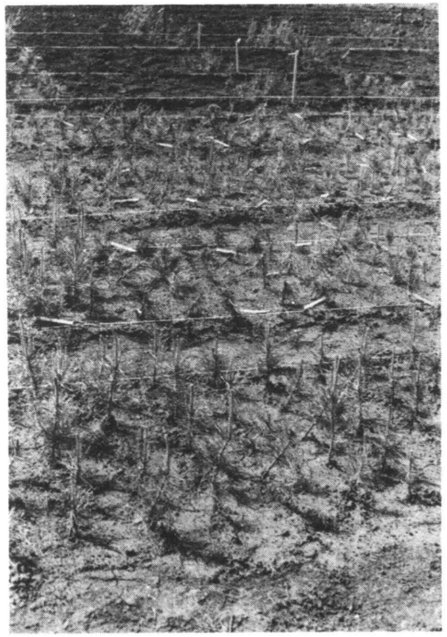

Figure 4.1. Homogenous nursery field was used as the planting site for experiments reported in Sections 4.2.1.-4.2.6.

tal conditions, should principally be viewed as a means of motivating a proper execution of the planting operation. To gain the attention of the people involved in implementing reforestation, the recommendation is printed on the polythene bags used for storing and transporting barerooted forestry transplants, for example on those described as Bag A and Bag B in Section 2. A universal relationship existing between the stress duration and the transplant performance is interpretable, using the concepts mentioned in Section 3, as a universally constant strain rate.

This experiment was designed in order to test whether the injury developed in barerooted Scots pine transplants after planting out in the field, would depend only on the **duration of the stress conditions prior to planting**, Δt_s. Symbol Δt_s was used instead of U to denote the variable which in the dynamic context would have been called accumulated strain. The ”accumulated strain”, U, is here defined as

$$U = \Delta t_s \tag{4.1.}$$

The stress treatment for this experiment was arranged in environments which included stress but which, at the same time, differed from one to another with respect to some stress conditions. All plants used in this study were barerooted 2+1 Scots pine transplants (Appendix 1).

Recently lifted plants, with unsheltered root systems, were exposed to stress for various periods of time. The treatment was carried out in three different environments which were called ”high”, ”moderate” and ”low” referring to the temperature:

High: +37±1°C

Moderate: +24±3°C

Low: + 2±1°C

This range of temperatures was considered realistic for the conditions of transplant storage and transport as was indicated by observations in Section 2.

Specially designed exposure tables were used for the stress treatment. At the beginning of the experiment, a number of 7, 4 and 5 sublots, in ”high”, ”moderate” and ”low” environments, respectively, were placed on a net of chicken wire laid over the top of the exposure tables. Each sublot was treated with a specific stress duration. A sublot consisted of 20 transplants, the total number of plants thus being 140, 80 and 100, respectively, for ”high”, ”moderate” and ”low” environments. Before placing the plants over the tables, each transplant was shaken lightly in order to detach the major soil clods from the roots. The exposure duration ranged from 1.5 to 11 hours, from 4.0 to 22 hours, and from 28 hours to 9 days, respectively, in the ”high”, ”moderate”, and ”low” environments. With prolonged exposures in the ”moderate” and ”low” environments it was assured that some injury to the plants was to be expected. Solar radiation was debarred in all the three environments. Temperature, however, was not the only factor which varied from one environment to the other. Water vapour deficit was highest in the ”high” environment and lowest in the ”low” environment.

After the exposure treatment the sublots were planted in an open nursery field following a standard procedure (Figure 4.2.). The soil was watered at planting in order to minimize the uncontrollable drought effect. Three reference lots, also consisting of 20 transplants, were planted in the same field. The injury variables, survival, I_s, and Growth Index, I_g, were determined after two growing seasons that is, after about one year and three months. The Productivity Index, I_p, was computed as well.

Injury variables, I_s, I_g, and I_p, were related to stress duration. Eqs. 3.10, 3.11 and 3.12 were applied substituting U by Δt_s. The parameters of the equations were estimated separately for data from the three environments.

Results

Survival decreased to half (s_{50} of Eq. 3.10.) in 5.4 hours, 12 hours and 50 hours in ”high”, ”moderate” and ”low” environments respectively. The Growth Index decreased to half (g_{50} of Eq. 3.11.) in 4.0 hours, 6.2 hours and 37 hours in ”high”, ”moderate” and ”low” environments respectively (Figure 4.3). The Productivity Index decreased to half (p_{50} of Eq. 3.12.) in 12 minutes, 40 minutes and 1.1 hours in ”high”, ”moderate” and ”low” environments, respectively[1].

Figure 4.2. Planting the trees in the nursery field.

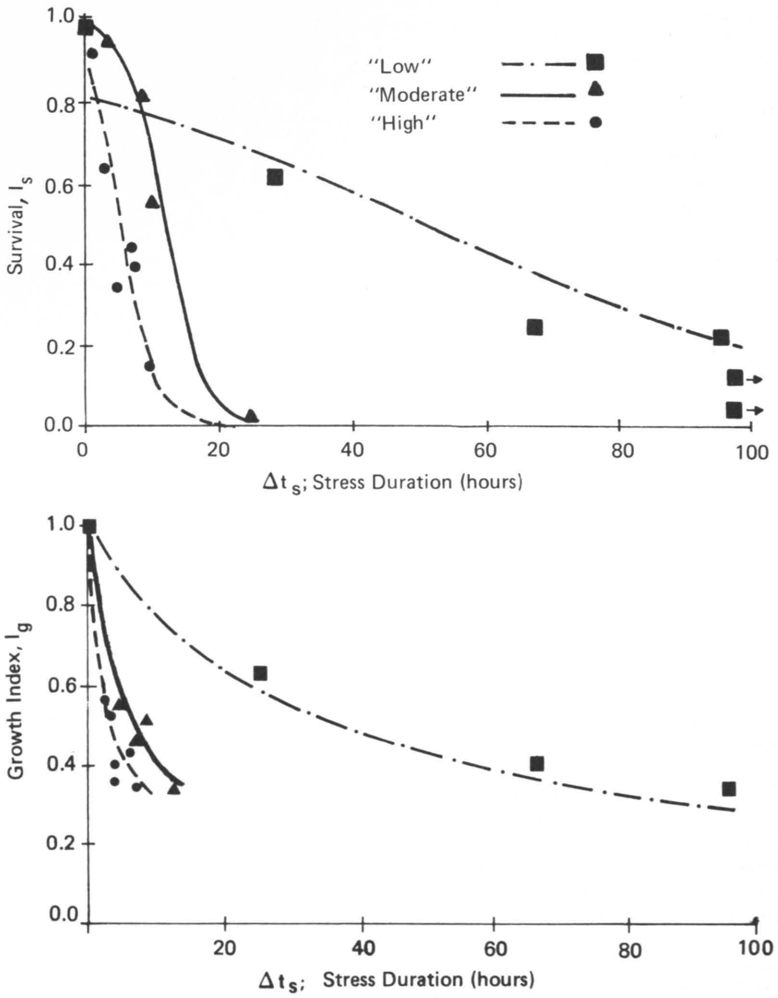

Figure 4.3. Survival (*top*) and Growth Index (*below*) of plants as functions of stress duration.

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[1] It turned out that the data were not quite satisfactory for estimating the Productivity Index. Observations tended to cluster around $I_p \sim 0.0$, except in the case of the reference lot, for which I_p by definition was 1.0. Therefore, in this experiment, and also in the experiments below, the estimated figures for p_{50} (Eq. 3.12.) are to be considered tentative.

The results strongly suggest that the strain rate would not be universally constant but, instead, it would substantially vary from one environment to another. This was indicated by both the survival and the Growth Index curves: Typically, for example, a given decrease in survival was reached in the "high" environment earlier than in the "moderate" environment, and in the "moderate" environment earlier than in the "low" environment. The following experiments are based on the view that strain rate is *not* universally constant. Efforts are made to link the established variability in the strain rate to a number of measurable stress variables.

4.2.2. Strain due to desiccation

With this experiment the variability in the strain rate was related to potential evapotranspiration which was measured by monitoring the evaporation rate of an open water surface (mm/hour), denoted as e. Hence, in terms of the Dynamic Injury Model, stress (see Equation 3.1.) is here developed as

$$s = s(e(t)), \qquad (4.2.)$$

Stress resistance was assumed constant; the term r of Eq. 3.3. was thus omitted. Further simplifications were implied considering that the plants would lose their vigor at a rate which is proportional to the rate that they get dry, and that the plants get dry at a rate which is proportional to the evaporation rate of an open water surface. Both of these assumptions are simplifications. They were taken as the first steps towards a replacement of the stress duration hypothesis of the preceding section. These assumptions gave rise to an operational measure of **strain rate due to evapotranspiration** u_e:

$$u_e = e(t). \qquad (4.3.)$$

The corresponding **accumulated strain due to evapotranspiration**, U_e, was then developed as:

$$U_e = \int_{t0}^{t_1} e(t)dt. \qquad (4.4.)$$

For simpicity, this integral, as a measure of accumulated strain, was called evaporation. The unit of accumulated strain due to plant desiccation was simply millimeters of water evaporized from a free water surface. U_e was monitored throughout the study directly by recording evaporation.

The empirical data were obtained from the same plants which provided the data for the experiment described in section 4.2.1. The environments were also called "high", "moderate" and "low", corresponding to the adjusted temperatures of 37°C, 24°C and 2°C, respectively. U_e was measured in these environments using the dish technique, *i.e.* monitoring the water surface level of a small dish with a surface area of about 300 cm^2 (Vaartaja 1954, Hari et al. 1975). One dish was used in each of the three environments. The dishes were placed among the transplants lying on top of the exposure tables. In order to improve the accuracy of measurement the surface level was recorded in terms of the weight of the dish (Hari et al 1975). The weight readings (grams/dish and measurement interval) were converted to readins of evaporation (mm per hour). The measurements of evaporation were related to the injury variables by inserting U_e for U into Eqs. 3.10.-3.12., and by estimating the parameters.

Results

Survival decreased to half (s_{50}) at U_e values 0.44, 0.52 and 0.21 mm in "high", "moderate" and "low" environments, respectively. The Growth Index decreased to half (g_{50}) in 0.40, 0.24 and 0.15 mm, respectively, in "high", "moderate" and "low" environments (Figure 4.4.). The Productivity Index decreased to half (p_{50}) with 0.019, 0.026 and 0.004 millimeters, respectively, for the three environments. In the "low" environment the injury seemed to develop at a somewhat faster rate, in relation to U_e, than in the "moderate" or "high" environments. Nevertheles, the results are more uniform than those in Figure 4.3. in which injury was related to stress duration.

A comparison was made between the power of stress duration, Δt_s, and that of evaporation, U_e, for explaining the variability of injury. Data from all three environments were put together. Eqs. 3. 10., 3. 11. and 3. 12. were fitted to the joint data set which now consisted of 7+4+5=16 sublots.

In the joint data set, in relation to stress duration, survival was halved in 28 hours, the Growth Index was halved in 5.7 hours, and the Productivity Index was halved in about 16 minutes. In relation to evaporation the corresponding paramaters were: s_{50}=0.39 mm; g_{50}=0.27 mm; and p_{50}=0.014 mm. The proportion of explained variance was computed for these two models. With stress duration as the independent variable the model explained 66 and 47 per cent of the variance for the survival and Growth Index, respectively. With evaporation integral, U_e, as the independent variable the corresponding figures were 74 and 73 per cent, respectively. Since the injury data were exactly the same, it can be concluded,by comparing the proportions of explained variance of the two models, that the evaporation integral was more powerful than stress duration in explaining the variability of injury variables. The approximation of the accumulated strain by U_e, is a step toward an improved understanding of the processes underlying the plant injury.

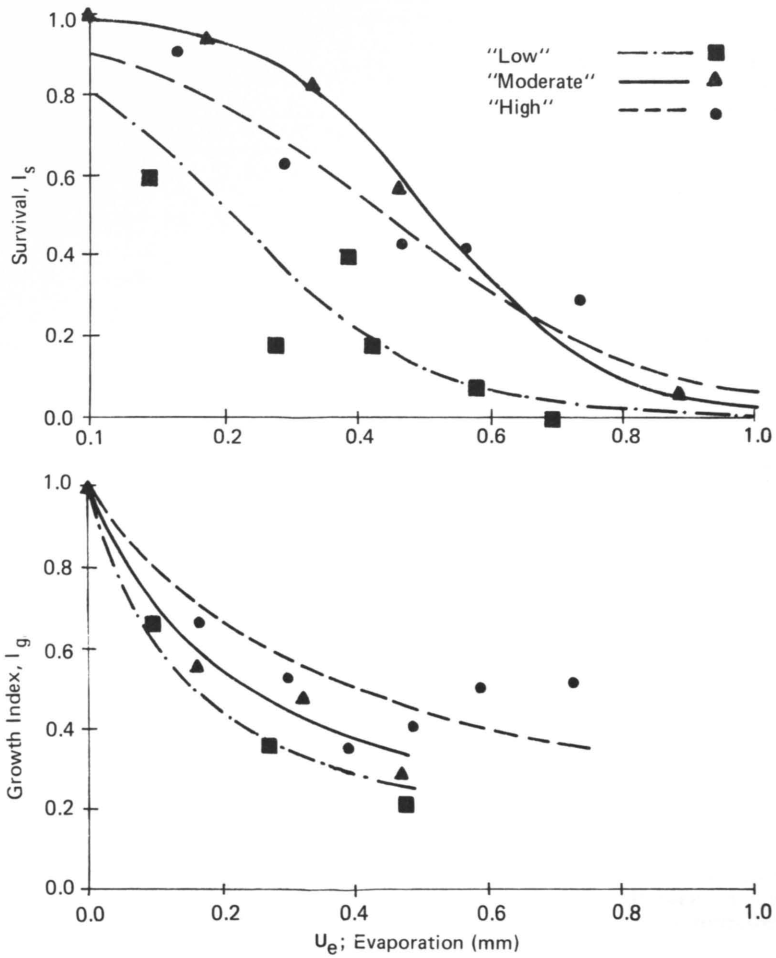

Figure 4.4. Survival (*top*) and Growth Index (*below*) of plants as functions of evaporation, U_e.

4.2.3. *Solar irradiance as stress factor*

The purpose of this experiment was to evaluate the role of solar irradiance as a stress factor. It is conceivable that plant roots are damaged when exposed to solar irradiation since roots have had no selection pressure in evolution, which would have modified them to cope with high irradiances. The injury could be due to *i)* direct stress of, most likely, the ultraviolet component of solar radiation, or *ii)* the indirect stress generated by excess heat and excess evapotranspiration (Levitt, 1972). This experiment was particularly designed to test whether or not the *direct* irradiance stress is significant. Accumulated strain due to solar irradiation was approximated in two different ways; one was to account for the direct stress and the other for the indirect stress.

Direct stress: The view was taken that the direct stress induced by solar radiation is proportional to the global solar irradiance, q (measured as W/m^2). Hence the **direct stress due to solar irradiance,** s_q, is:

$$s_q = q(t). \qquad (4.5.)$$

Stress resistance was again assumed as constant. **Strain rate due to solar irradiance,** u_q, was thus obtained as:

$$u_q = s_q = q(t). \qquad (4.6.)$$

This approximation of strain rate was used to compute **accumulated strain due to solar irradiation,** U_q:

$$U_q = \int_{t_0}^{t_1} q(t)dt. \qquad (4.7.)$$

The strain, U_q, solar irradiation, was related to injury data.

Indirect stress: The indirect stress due to solar irradiance was assumed to be proportional to the evaporation rate of an open water surface. This was based on the consideration that in sunny environments solar irradiation enhances evapotranspiration as compared to the rate prevailing in shaded environments. The indirect stress was thus introduced into the analysis in the way described above in Eqs. 4.2−4.4.

Three experimental structures were arranged on an open sward with different environments appropriate to the observation of direct and indirect stress. Sublots of plants (see Appendix 1) were placed on exposure tables in the same way as was done in experiment 4.2.1. In the first environment, called "shadow", the plants were protected from solar irradiation by using plywood sheets located 20–50 cm above the transplants. Within the shadow of the sheets the global solar irradiance was less than 5 per cent of that in other parts of the sward. Substantial evapotranspiration, however, occurred in this environment. Thus, although the plant temperature was obviously lower than it would be in sunlit conditions, the transplants were subjected to a stress similar to the indirect stress due to solar irradiance.

In the second environment, "shower", within 15 meters of the first one, plants were subjected to direct stress only. Solar radiation entered the plants but evapotranspiration and excess heat were debarred. This was arranged by supplying a continuous water spray into the air right above the plants. The air immediately above the tables was saturated with water vapor since the water spray was directed from one side of the table to the other at a height of 10–30 centimeters above the transplants. The water spray absorbed less than two per cent of the global solar irradiance. Given the transmittance spectrum of water (Goody & Robinson, 1951) the fraction absorbed was even less in terms of UV-radiation.

In the third environment, "sun", within 15 meters of the other two, the transplants were freely subjected to both the direct and indirect stress. The plants were placed on top of the exposure tables without protecting them in any way (Figure 4.5.).

Sublots, each consisting again of 20 transplants, were exposed to the stress. In the beginning of the experiment all sublots were simultaneously placed on the exposure tables. As the exposure passed on, the sublots were planted one at a time after the predetermined period of exposure was reached. The number of sublots in the "shadow", "shower", and "sun" environment was 7, 7 and 4, respectively. The duration of exposure ranged in "shadow", "shower" and "sun" environments from 40 minutes to 22 hours, from 1 to 56 hours, and from 40 minutes to 5 hours, respectively.

Solar irradiance was continuously measured and registered using a Lambda LI pyranometer and a millivolt recorder. The irradiance up to the end of each exposure period was integrated from the recorder graph. This integral provided the measure for U_q of Eq. 4.7. Two dishes were filled with water and placed among the plants, one in the "shadow" and the other in the "sun" environment. The dishes were weighed at the end of each exposure dosage. The readings, interpreted as U_e as in Eq. 4.4., provided the measures for the indirect stress.

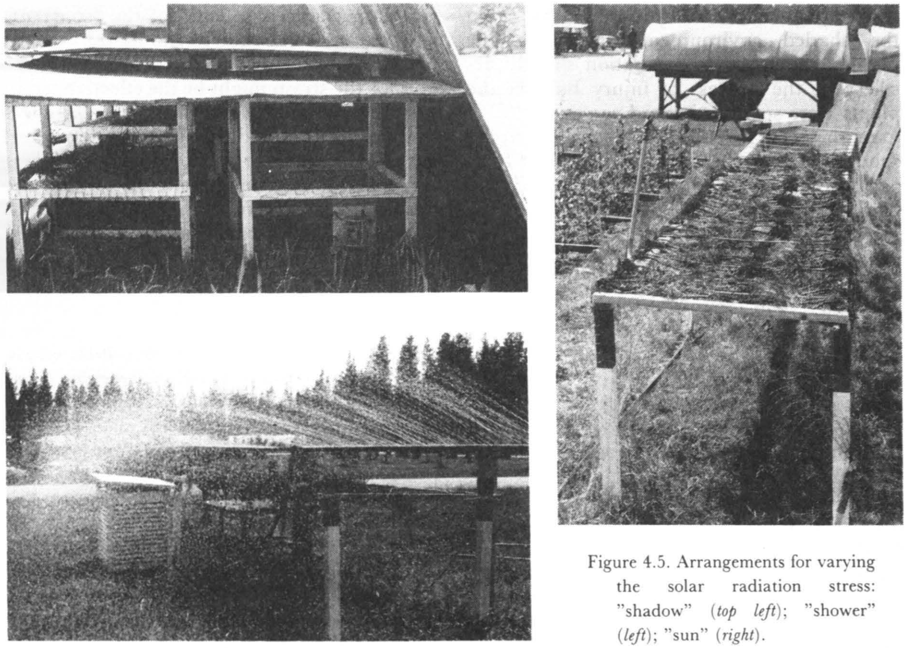

Figure 4.5. Arrangements for varying the solar radiation stress: "shadow" (*top left*); "shower" (*left*); "sun" (*right*).

Exposure was started on the 14th of June, 1977, at 9.00 A.M., and the following three days were particularly sunny and dry. A rain gauge was located 80 metres away from the experiment tables, and temperature was monitored in a shade right next to the plants. The total precipitation over the exposure period was less than 0.5 mm. The temperature during the 56 hour exposure period ranged from 16 to 31 °C. The sky remained cloudless for most of the time. The solar irradiation for the 56 hour exposure period was 63.0 MJ/m², corresponding to an average irradiance of 310 W/m² for both day and night. (This figure is close to its maximum value not only in Finnish conditions but also throughout the world (Budyko, 1963). The high figure is due to the sunny weather and to the long day in the high latitudes at this time of the year). Planting and raising the transplants, as well as measuring the injury variables, was done following the standard procedure (Appendix 1). Injury variables, I_i, I_g and I_p, were then related to the two variables which approximated the accumulated strain, U_q and U_e. Equations 3.10., 3.11. and 3.12. were fitted to the data.

Results

Exposure to solar irradiation did not cause any injury when the transplants were protected from desiccation and excess heat. The transplants exposed to "shower" for 56 hours grew as vigorously as the reference plants. As none of the plants died, the Productivity Index also remained at the level of 1.0 throughout the whole range of treatments. In contrast to these results all the plants died when exposed to the environment "sun" for just 5 hours. The injury was obvious also in the "shadow" environment: only 3 out of 20 plants survived the exposure of 22 hours. The results provided a clear answer to the question of the direct *versus* the indirect stress due to solar irradiance. Unprotected plants were severely injured. The injury was due to *indirect* irradiance stress. When debarring desiccation and excess heat, direct irradiance stress appeared to be of no significance. The result was confirmed by observations from the shaded environment. Protecting the plants against direct irradiation slightly decelerated the process of injury but yet the plants were severely injured.

As the plant response was negligible in the "shower" environment Equations 3. 10.–3. 12. could not be fitted to those data. Regarding the other two environments the results were the following. Survival decreased to half (s_{50}) at evaporation integrals (U_e) of 1.86 mm and 1.35 mm respectively, in "shadow" and "sun" environments. The Growth Index decreased to half (g_{50})at evaporation integrals of 0.49 mm and 0.42 mm, respectively. The Productivity Index decreased to half (p_{50}) at evaporation integrals of 0.05 and 0.03 mm in "shadow" and "sun" environments respectively (Figure 4.6.). In the "shadow" environment the plants appeared to tolerate heavier dosages, in terms of the evaporation, than in the "sun" environment. Moreover, the plants in both environments seemed to possess a higher stress resistance than the plants in the above experiments (see Figure 4.4.). The difference, however, can be due to other factors, such as uncertainty in evaporation measurements.

4.2.4. High temperature stress

In large scale tree planting programs it is possible that high temperatures can not always be avoided. In some cases high temperatures bring about high evapotranspiration rates. But high temperatures can also occur in conditions where evapotranspiration is negligible, for example when the increase in temperature is due to plant metabolism inside the sealed bags (Rikala, 1983). This experiment was designed to test the significance of high temperatures as a stress factor in addition to evapotranspiration.

A fixed period of time was chosen for the stress treatment. The magnitude of stress did not vary within the time period of the exposure. For this type of experiment design, the Dynamic Injury Model is not neccessarily needed. Dose-response relationships can be derived by plotting the injury figures against the temperature figures. The dosage, however, can be interpreted also in terms of the Dynamic Injury Model. Accumulated strain is obtained as the integral of the (constant) temperature over the (constant) duration of the stress exposure. Theoretically, a proper unit for the strain might be the effective temperature sum, jointly determined by the effective temperature and the stress duration (e.g. Sarvas, 1972). Since the duration of the stress was fixed in this experiment the level of the strain, T, is given simply in terms of temperature (as °C). The experiment was conducted in the following way.

Plants were subjected to stress in a heated, dark chamber with a relative humidity of ~ 100 per cent. With this arrangement it was possible to debar evapotranspiration. The twenty transplants belonging to one sublot were laid on shelves of the chamber after the temperature had reached the required value. The treatment lasted for ten minutes, the transplants were then cooled down to a temperature of +2°C, and the chamber temperature again adjusted for the next treatment. Two similar experiments were carried out, the first one on the 16th of May, and the second on the 25th of May 1977. In the first experiment, six temperature levels were used within the range 25–58°C. In the second experiment, five temperature levels were used in the range 35–55°C.

The treatment chamber was located at the Finnish Pulp and Paper Research Institute (Keskuslaboratorio) in Otaniemi, at a distance of 340 kilometers from the Suonenjoki Experimental Station where the plants were grown. The time required for lifting, packing, transportation to Otaniemi, stress treatment, and transportation back to Suonenjoki was 34 to 42 hours for the first and second experiment respectively. During transportation which was done by rail and road, the plants were packed in cooled wooden containers in order to mitigate additional stress. Two groups of reference plants were used in these experiments; one (control A) consisting of plants which had been subjected neither to a stress exposure nor to the transportation and the other (control B) of plants which had been transported on the route Suonenjoki–Otaniemi–Suonenjoki, but had not been subjected to the stress exposure. Otherwise the experimental layout followed the standard procedure (see Appendix 1).

Results

An abrupt increase in mortality was found to occur within the temperature range +45–+55°C. All the reference plants, and plants exposed to +45°C or lower temperatures survived. Growth also maintained at the control level up to this critical range of temperatures (Figure 4.7.). The growth of the transported plants (control B) appeared to be smaller than that of the reference plants (control A) which had not been moved, although the reduction due to transportation was no greater than a few per cent. Survival with both of the reference stocks was 100 per cent.

It is worth emphasizing that the plants were subjected to the stress only for ten minutes. Damage would occur also in lower temperatures than those observed in this experiment, if more time were given for the strain to build up. Such slowly developing strains are, for example, due to gradual loss of carbohydrates (Puttonen, 1980). With this experiment design it was possible to address only abrupt strains such as dehydrolysation of plant proteins (Levitt, 1972). It appeared that for such an abrupt strain the threshold temperature is about +50°C.

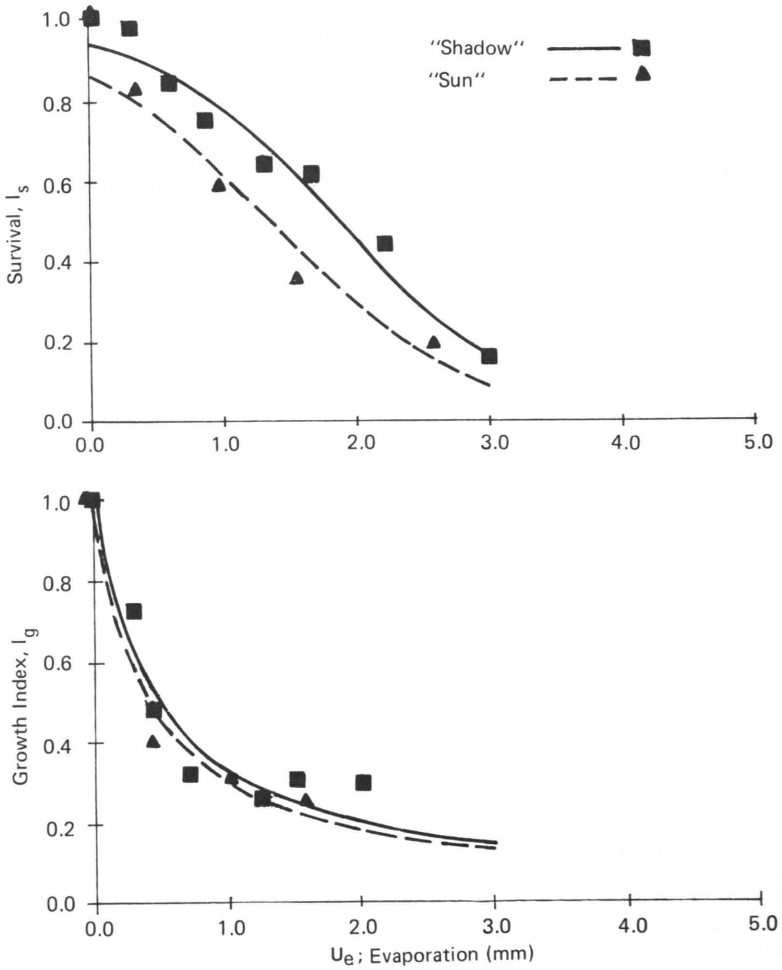

Figure 4.6. Survival (*top*) and Growth Index (*below*) of plants as functions of evaporation, U_e.

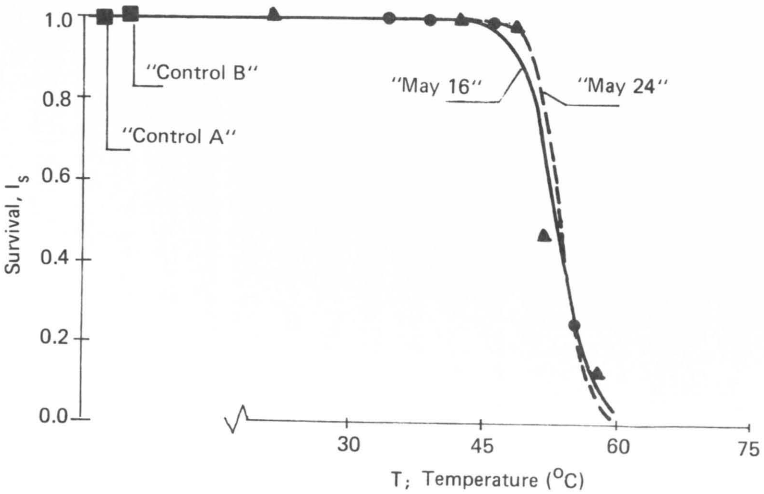

Figure 4.7. Survival of plants as a function of stress temperature.

4.2.5. Vibration and dropping during handling

When being transported from one place to another tree transplants can be subjected to mechanical stress such as pressure in a fully packed truck, vibration of the vehicle, dropping of the plant containers from the truck onto solid soil, etc. Mechanical stress was studied in two experiments. An experiment was carried out in Otaniemi using a vibration table designed by the Finnish Pulp and Paper Researh Institute for truck transportation simulations. A regulated amount of vibration was given to plants which had been placed in polythene bags. In the dropping experiment, transplants in similar polythene bags were allowed to fall freely from an aircraft onto a solid soil surface. With dropping from the aircraft the stress was not quantified. The intention, however, was to exaggerate the stress of forestry practice, and this goal was most likely achieved (Figure 4.8.).

The transportation simulator was a 3 m^2 table, which was moved in an up-and-down direction. The acceleration of the motion in the vertical direction followed a sine function. The vibration stress was expressed in terms of the maximum acceleration, the level of which was adjusted by controlling the frequency and the amplitude of the motion.

Transplants were laid on the table in a polythene bag placed in a wooden 80×60×60 cm box. Twenty transplants were used for each acceleration level. The plants were packed in the polythene bag with Scots pine branches used in order to simulate the missing 200–400 plants of a fully packed bag. The bag was placed at the bottom of the box, and three bags were placed on it, each filled with pine branches to a total weight of 20 kilograms. When treating a sublot the frequency and the amplitude of the motion were kept constant. Each sublot was treated for 5 minutes. For the next sublot, new acceleration level was adjusted.

The induced strain was denoted by U_a (strain due to acceleration). The peak values of acceleration ranged, in 9 levels, from 1.0 to 51.0 m·s^{-2}. The highest level was achieved by shaking the table 600 times a minute with an amplitude of 13 mm. After the treatment the plants were handled according to the standard procedure (Appendix 1). The injury variables, I_r and I_g, were measured.

In the dropping experiment four polythene bags were filled with 90 experimental plants and 150 plants were added in order to increase the bag weight. Four bags were used, the total amount of experimental plants thus being 360. Sealed bags were allowed to fall from a height of about 35 meters from a flying aircraft onto a road near the runway. The bags were picked up and again dropped from the aircraft in a similar way two more times. Some of the bags ruptured. The torn bags were replaced with new ones in between the treatments. The airport was located 40 kilometers from the Hyytiälä Forestry Station, and the time taken for which the plants were outside storage conditions was 2 hours 40 minutes. With the dropping experiment, unlike the other experiments of this study, only mortaility was surveyed. Moreover, the survey was done at the end of the first growing period after planting (Appendix 1).

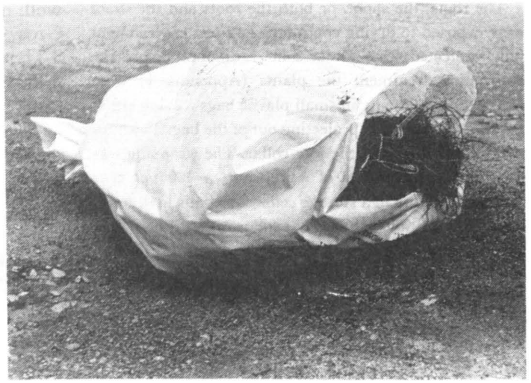

Figure 4.8. When dropped from the aircraft (*left*), the transportation bags frequently ruptured (*right*).

Results

All the shaken plants survived, irrespective of the vibration dosage. Using the available routines it was not possible to fit the Eqs. 3.11 and 3.12, because the values of the Growth Index and the Productivity Index were practically constant. It appears unlikely that shaking of this kind would induce a strain in the transplants. In the dropping experiment 50 per cent of the plants survived. Given that the treatment of the plants was rather tough in both experiments it is concluded that the Scots pine transplants are relatively tolerant of shaking and dropping.

4.2.6. Shoot versus root desiccation

The experiments above indicated that desiccation of the plant, induced by high rates of evapotranspiration, would be a severe source of strain as compared to strains induced, for example, by the direct effect of solar radiation or vibrations. Therefore, the following experiment was established in order to study the desiccation in more detail. The intention was to compare the strain due to desiccation of the plant shoot to that due to desiccation of the plant root. Within the framework of the Dynamic Injury Model, the question of the stress resistance of the tree shoot being greater than that of the tree root was examined. Such a hypothesis would appear reasonable, since due to evolution, plant shoots have mechanisms such as stomata to conserve water, whereas such mechanisms are lacking in roots. The low desiccation resistance of roots has earlier been documented by Coutts (1981), and Parviainen (1982).

The roots, the shoot, or both the roots and the shoot were exposed to drying conditions in a test environment fully protected from direct solar radiation. Before the desiccation treatment the plants (Appendix 1) were wrapped individually in small plastic bags leaving either the shoot or the roots projecting out of the bag. The bags were sealed tightly at the root collar. The wrapping was done at a temperature of +5°C and ~ 100 per cent relative humidity in a storage cellar for plants in order to minimize additional stress. The following day the plants were transferred to the exposure environment. They were spread on the exposure table together with fully exposed transplants. The plants were removed from the table when predetermined U_e values had been reached.

The root-to-shoot ratios were determined from a sample of 50 plants on dry weight basis. In addition, a sample of 16 plants was used to measure the root-to-shoot ratio in terms of surface area. In this method the plants are immersed in a solution of calcium nitrate, $Ca(NO_3)_2$. The bowl containing the solution rests on a balance. The surface area of the plant material is approximated as the decrease in the weight of the bowl following the immersion (Carley and Watson, 1966; see also Lähde and Oksanen, 1969). This is based on the assumption that all types of surfaces collect the solution with constant efficiency. – The mean root-to-shoot ratio was 0.26 on a dry weight basis. On the surface area basis the mean root-to-shoot ratio was 0.27.

In order to increase the accuracy of measurement, evaporation was monitored using four water dishes and, in addition to them, three Piche evaporimeters (cf. Odin 1976). The evaporimeter measurements were calibrated using the readings from the water dishes so as to obtain the U_e values in millimeter units. The strain, U_e, was determined, as in Eqs. 4.2.–4.4., as the average of the results of the seven instruments. The number of strain levels was six within the range 0.1–6.7 mm. The transplants were planted out in the nursery field. Injury variables, I_s, I_g and I_p, were related to evaporation, U_e, separately for the three groups of plants that is, for the unprotected group, for the group with protected roots and the group with protected shoots. Equations 3.10, 3.11, and 3.12 were fitted to the data.

Results

An increasing degree of damage with prolonged stress exposure was observed with all three groups of plants. The survival decreased to half (s_{50} of Eq. 3.10.) with U_e values of 1.0 mm, 2.1 mm and 12.5 mm for unprotected, shoot protected and root protected plants respectively. In this experiment as well, none of the 60 reference plants died. The Growth Index decreased to half (g_{50} of Eq. 3.11.) with evaporations of 0.5, 1.1, and 15.0 mm, respectively (Figure 4.9.). The Productivity Index decreased to half (p_{50} of Eq. 3.12.) with evaporations of 0.2, 0.4 and 4.4 mm, respectively.

These results indicate that the stress resistance of the shoot would be roughly one order of magnitude greater than that of the root system. The difference is even larger on a unit area basis, i.e. when a unit of needle area is compared to a unit of root area. As the shoot was larger than the root by a factor of 2.5–2.8, the stress resistance of the shoot, on an unit area basis, would be about 20 times greater than that of the root. As the roots of barerooted plants have low stress resistance, it is important in practise to ensure that the surroundings of the root are protected. The shoots could even be subjected to the open air in order to control high temperatures which tend to occur in all sealed environments. Yli-Vakkuri (1957) reports on a transportation container of this type. Taking that idea and adapting it rationally to meet modern demands might provide an improvement in forest regeneration practices.

4.2.7. Injury modified by the surrounding tall stand

In the above experiments trees were planted in a nursery field. In order to be able to generalize the results, it is important to establish experiments in different field environments. This experiment as well as the one reported in the following Section 4.2.8. was conducted in order to study how site environment modifies injury development. The focus is thus shifted from Eq. 3.5. to Eq. 3.6.

A tall stand surrounding a forest opening produces a gradient in the solar radiation within the opening, especially near the southern edge of the opening (Fischer, 1974). The radiation gradient obviously causes secondary gradients in the temperature climate and soil properties. The gradient of decreasing tree root competition also exists from the edge of the surrounding stand towards the center of the opening. However, in the competition between other plant species the direction of the gradient is the reverse. Nevertheless, it is unlikely that the partially counteracting gradients would result in a zero effect on plant growing conditions. Indeed, Jackson (1962) reports statistically significant changes of plant morphology together with such gradients.

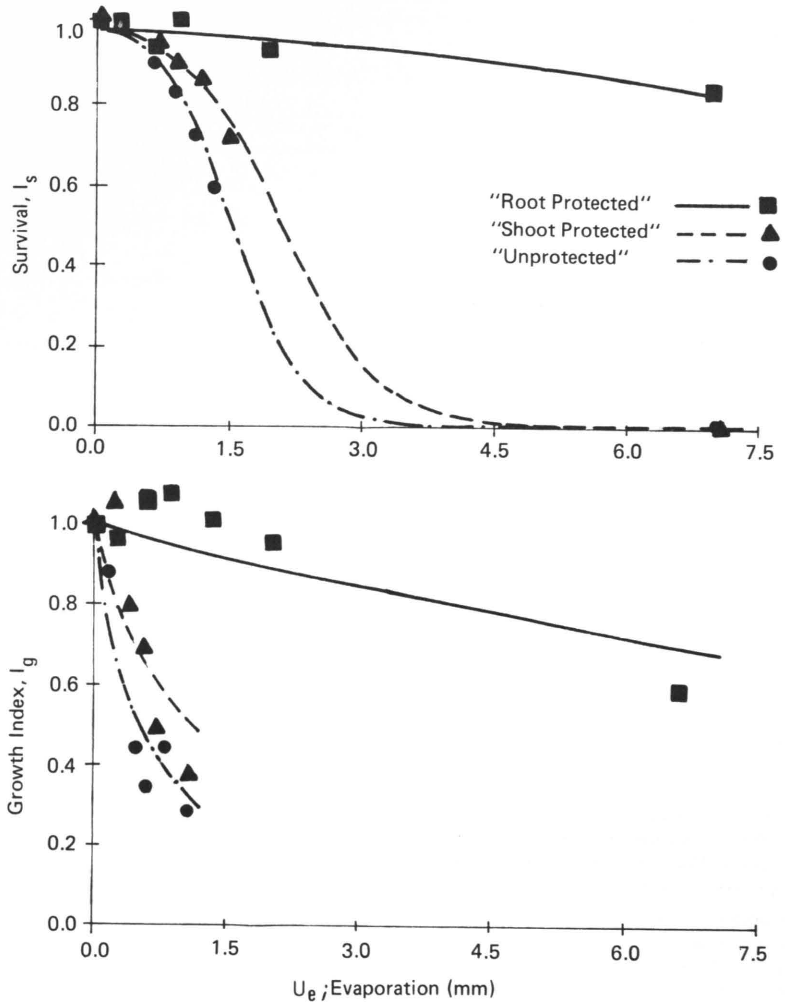

Figure 4.9. Survival (*top*) and Growth Index (*below*) of plants as functions of evaporation, U_e.

In this experiment stressed and nonstressed Scots pine transplants were planted along lines passing northwards from the southern edge of two forest openings. The transplants were thus placed at different points along the environmental gradients. The aim of this experiment was to study whether a given amount of strain, originally induced by a controlled stress exposure prior to planting, would result in different levels of injury in different parts of the environmental gradients.

Trees were planted in two forest openings which were situated at a distance of about four kilometers from the Hyytiälä Forestry Station. The first opening was a dry heath, a clearcut area of Scots pine. Hereafter this opening is called "dry". The second opening was a moist upland site, a clearcut area of Norway spruce. This opening is called "moist". The "dry" opening was typically suited for planting only Scots pine whereas for the "moist" opening Norway spruce would have been an alternative tree species. The "dry" opening was surrounded by a Scots pine stand, with a height of 14 meters, and the "moist" opening by a Norway spruce stand, with a height of 20 meters.

The stressed transplants were divided in two treatment categories in which they were exposed to desiccation of two evaporation levels, 0.2 mm and 0.4 mm. The exposure was conducted in environments protected from direct solar radiation. The stressed and nonstressed transplants were planted along two lines stretching northwards from the southern edge of the two openings. Along with the lines, at a given distance from the edge of the stand, four transplants were planted in the form of a compact cluster. One of the plants was treated with U_e = 0.2 mm, one with U_e = 0.4 mm, and the two others were nonstressed reference plants. Each cluster had a specific location in relation to the stand, the idea being that within the cluster each plant had an identical location in this respect. The first cluster in the line was located right at the edge of the surrounding stand. The most distant cluster was 20 meters and 42 meters in the line from the edge of the stand in the "dry" and "moist" sites, respectively. The number of clusters per line was 25 and 50 on the "dry" and "moist" openings, respectively. The typical interval between two clusters was thus less than one meter. The total number of plants used in this experiment was 600. Unlike in the nursery field experiments, the plants were not watered at planting.

The location of transplants was not fixed in advance, which made it possible to select a favourable place for every plant. The position of each cluster was determined by measuring the angle from the horizontal plane at plant height, to the top of the nearest trees of the stand surrounding the opening. This variable, assuming that the edge of the surrounding stand is straight, is linearly related to the fraction of the hemisphere which is covered by the tree canopies (Norman & Jarvis, 1975). It was taken as an operational measure for E of Eq. 3.6. Survival, I_s, and Growth Index, I_g, were measured after two growing seasons.

Special arrangements had to be made to obtain values for the Growth Index from this kind of data. Starting from the edge of the stand, 6 to 10 clusters, depending on the number of survivors, were grouped together. The mean Growth Index was calculated for all such groups, and this mean was plotted against the mean position of the group.

Results

No clear trend was observed in transplant survival in the direction of the lines. Average survival seemed to be the highest with the U_e = 0.2 mm plants on the "dry" site and the lowest with U_e = 0.4 mm plants on the "moist" site (Table 4.1.). Neither did the Growth Index results indicate a modifying effect of the surrounding stand on the injury. The Growth Indices for the plants subjected to U_e = 0.2 mm were about 0.7 and 0.5, respectively, for the "dry" and the "moist" sites. The respective figures for transplants subjected to U_e = 0.4 mm were about 0.4 and 0.15. The injury due to the stress treatment appeared to be independent of the position of the plant within the environmental gradients (Figure 4.10.).

4.2.8. Injury development on miscellaneous sites

Another experiment was carried out in order to compare the injury development in different environments. Equation 3.6. was used again that is, both the strain and the site environment were included as variables. In this case, however, the differences in site environment were not due to a specified gradient; sites differed from one to another only in qualitative terms. The differences were not measured based on environmental variables. Another approach was used instead. A "biological site index" was defined as the leader shoot elongation, in centimetres, of the nonstressed plants after planting. The injury was related to this index.

Table 4.1. Survival of nonstressed and stressed plants on two different sites.

Site	Survival, %		
	Reference	U_e=0.2 mm	U_e=0.4 mm
"Dry"	90	96	76
"Moist"	88	73	47

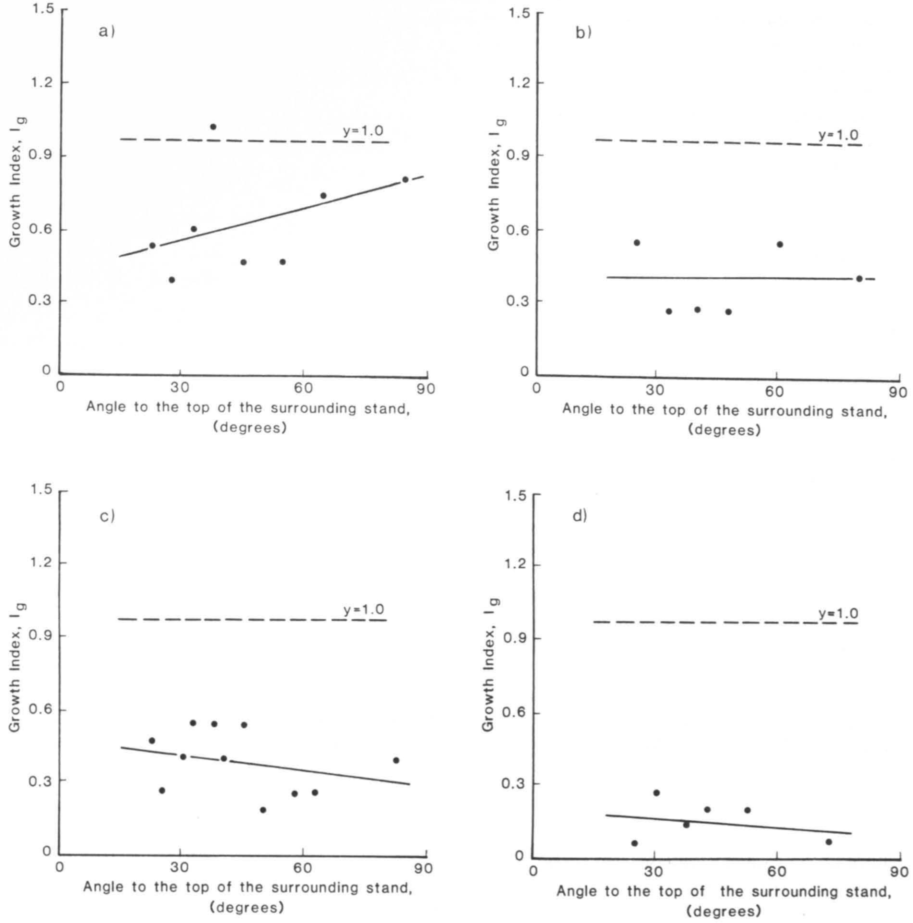

Figure 4.10. Growth Index as a function of the position of the plant in relation to the surrounding stand: *a*) "dry" site, U_e=0.2 mm; *b*) "dry" site, U_e=0.4 mm; *c*) "moist" site, U_e=0.2 mm; *d*) "moist" site, U_e=0.4 mm.

All the sites were located within ten kilometers of the Hyytiälä Forestry Station. In brief, the sites were as follows:

0. An approximately 200-square-meter opening in an agricultural field afforested 6 years before this experiment, *Calamagrostis* vegetation; mineral soil.
1. Open nursery field; a 25-centimeter-layer of surface soil replaced by sand.
2. Open field same as site 1; original surface soil (a mixture of mineral soil and peat).
3. Greenhouse with single glass cover but with no artificial heating; fertilized horticultural peat irrigated to maintain sufficent water supply.
4. Forest opening of a moist upland site, *Epilobium angustifolium* vegetation; mineral soil.
5. Same as site 4 but with no major herbs or grasses, *Ceratodon purpureus* as the dominant vegetation.
6. Forest opening of the very dry CIT site type (Cajander 1949), sparse *Vaccinium vitis-idaèa* vegetation; mineral soil.
7. Forest opening of moist upland site, subjected to

prescribed burning two years before this experiment, very sparse sprouting vegetation; mineral soil.

8. A 50-square-meter opening in a 15 year old birch-willow stand growing on a ploughed, peatland site, vigorus *Epilobium-Calamagrostis* vegetation; peat.
9. Forest opening of moist upland site subjected to prescribed burning two year before the experiment and to ploughing one year before the experiment, very sparse sprouting vegetation; mineral soil.

A set of hundred transplants was planted at each of the ten sites. This set comprised of five groups of plants which were treated before planting in the following way: Group *1*) was subjected to desiccation corresponding to U_e = 0.35 mm. Group *2*) received a prolonged desiccation exposure corresponding to U_e = 0.8 mm. Group *3*) was kept in open polythene bags in a dark, indoor environment, at a temperature of +22°C. Only the shoots of the transplants were in free air, the roots being protected in the bottom of the bag. During the treatment (from the 15th to the 21st of May) the bags were watered daily to a constant weight. Group *4*) was treated the same way except that they were kept at a temperature of +22°C for three more days. The respective effective temperature sums (defined also as 'heat sum' by Sarvas (1972)) for the groups *3*) and *4*) were 105 and 150 degree days. The aim of these two treatments was to generate a strain in the plants due to consumption of the carbohydrate reserves (Puttonen, 1980). Group *5*) was that of reference plants. Each of these five groups consisted of 20 transplants. The whole set of 100 plants was planted on a given site within one day. The transplants were not watered at planting. The planting dates for the different sites varied between May 24 and June 2, 1979 (Appendix 1).

Survival and leader shoot length were measured after two growing seasons. The Growth Index, as defined above, was inappropriate in this experiment because the "biological site index" was applied. Analysis was done using a method modified from the study of Finley and Wilkinson (1963). The mean growth of the stressed plants was related to that of the nonstressed plants. Only the survivors were included to form the mean. When plotted on a figure the data from poor sites appears close to the origin. On fertile sites, where the reference plants grow fast, data appears further apart from the origin. The strain effect with the stressed plants is indicated as data points below the line $y = x$. *A* linear regression was fitted to the data.

Results

A characteristic feature of this experiment was that all reference plants did not survive. On site Nr 4 as many as six out of 20 reference plants died (Table 4.2.).

Storage at room temperature prior to planting appeared to result in substantial mortality only on one site (Nr 8). Obviously, the food reserves were not severely exhausted which indicates that the plants must have been in good condition before the stress treatment. These observations are in agreement with the view that conifers are rather flexible in their carbon metabolism (Glerum, 1980).

Table 4.2. Survival of nonstressed and stressed plants on ten sites

Site nr	Plant survival, %				
	Reference	Storage at room temperature, 6 days	Storage at room temperature, 9 days	U_e=0.35 mm	U_e=0.35 mm
0	75	80	90	35	5
1	100	90	95	90	35
2	95	85	90	70	30
3	80	100	90	50	35
4	70	90	80	60	50
5	90	80	95	90	40
6	90	85	80	75	55
7	80	90	95	55	35
8	80	55	50	45	65
9	80	100	95	85	60
x̄	84	85.5	86	65.5	41

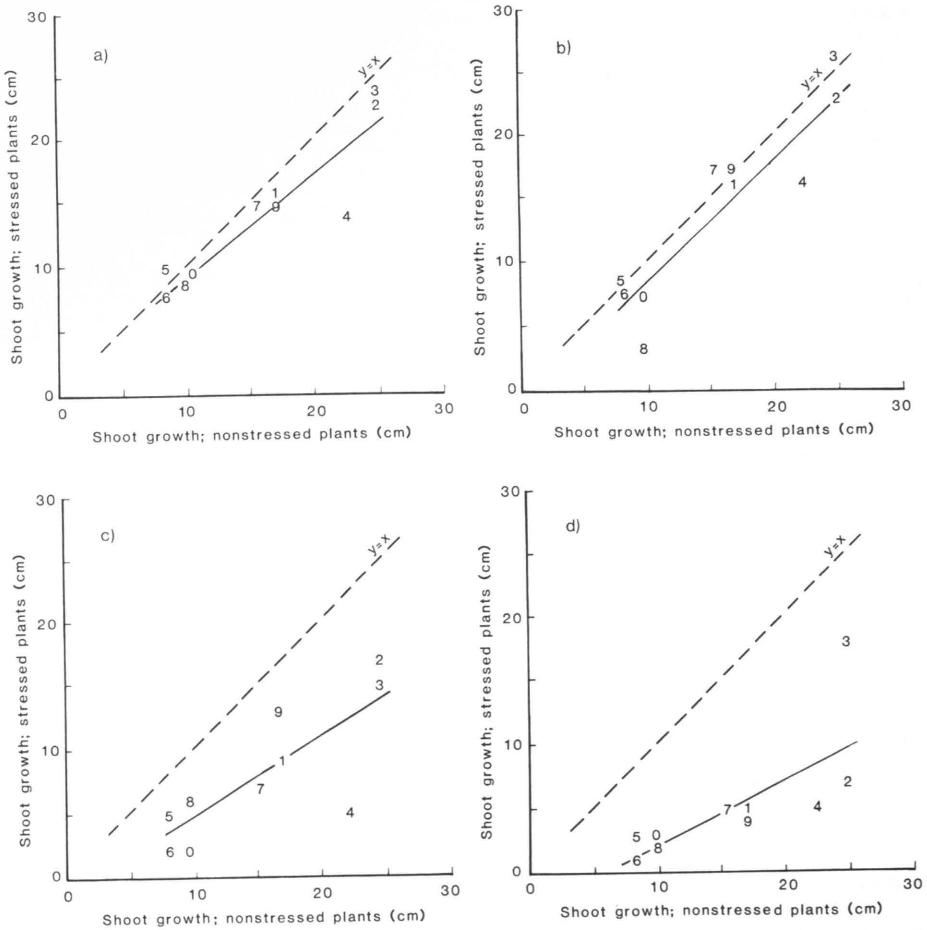

Figure 4.11. Leader shoot growth of the stressed plants as the function of that of the reference plants. The x-axis can be interpreted as the scale of the "biological site index". Numbers in the figure refer to the site. *a*) stress at room temperature, six days; *b*) stress at room temperature, nine days; *c*) evaporation, U_e=0.35 mm; *d*) evaporation, U_e=0.8 mm.

Desiccation level U_e = 0.35 mm seemed to decrease the survival of the plants on eight sites. The two exceptions were site Nr 5 in which the survival was 90 per cent for both the reference stock and the stock exposed to the 0.35 mm strain level, and site Nr 9 where survival figures were 80 and 85 per cent for the reference plants and stressed plants, respectively. Damage caused by *Hylobious abietis* was observed in plants on site Nr 9. At U_e = 0.8 mm strain level individual plants survived but, in general, the survival values of these sublots were substantially lower than those of the reference stock on every site.

Injury due to the "room temperature stress" (depletion of carbohydrates) seemed to be unimportant also in terms of growth (Figure 4.11.). The variation in the shoot growth of both stressed and nonstressed plants was clearly dominated by the site factor. The desiccation stress, in turn, appeared to cause a more severe strain and to decrease the shoot growth. Growth reduction was observed on every site even with the lower strain level of U_e = 0.35 mm.

The average survival, 65.5 %, following U_e = 0.35 mm was lower than that of the nonstressed plants (84 %). The difference is statistically significant (t-test; 2 per cent risk level). Moreover, the results indicate that the proportional decrease in growth, due to the stress exposure, is similar over a wide range of different sites. Conditions on either the poor or the fertile sites did not appear to compensate for the strain effect.

4.3. Concluding remarks

The strain induced through desiccation was measured consistently in all the experiments (for U_e, see Eq. 4.4). Further, injury measurements were uniform throughout most of the study. It is thus possible to combine the data from all experiments in which the strain was induced through desiccation, and to estimate the strain-injury functions, Eqs. 3.10.−3.12., for the combined data set. This is done below for those experiments in which the trees were planted in an open nursery field. A number of 31 data points are included in the combined data set. The data are obtained from experiments reported in Sections 4.2.2., 4.2.3. and 4.2.6. Only such data are included in which the whole plant was subjected to desiccation. Estimation resulted in the following functions:

Survival:

$$I_s = \frac{e^{-2.45(U_e-1.24)}}{1+e^{-2.45(U_e-1.24)}} \tag{4.8.}$$

Growth Index:

$$I_g = \frac{0.375}{0.375+U_e} \tag{4.9.}$$

Productivity Index:

$$I_p = \frac{0.037}{0.037+U_e} \tag{4.10.}$$

Survival thus decreased to half (s_{50}) with evaporation of 1.24 mm and the Growth Index with the value 0.37 mm (Figure 4.12.). The Productivity Index decreased to half (p_{50}) in U_e=0.04 mm. The functions estimated from the combined data set can be taken as the best estimates of the strain-injury relationship regarding desiccation.

The results of this study should be viewed in a broad perspective considering all subsequent phases of the forest regeneration process (Räsänen, 1981). Such an integrated analysis may indicate deficiencies in the phases of transfering the plants from the forest nursery into the field. If that is the case then this study provides information for upgrading the methods. The main focus should be given to protecting plant roots. The roots should be kept covered on all possible occasions. Additional measures are needed because covering the roots does not prevent all desiccation. Plants should be stored in places where the level of evapotranspiration is low. Evapotranspiration is difficult to monitor in the field. Basic physical laws confirm that high evapotranspiration rate is frequently associated with high temperature. Controlling high temperatures thus serves as an indirect method for controlling root desiccation.

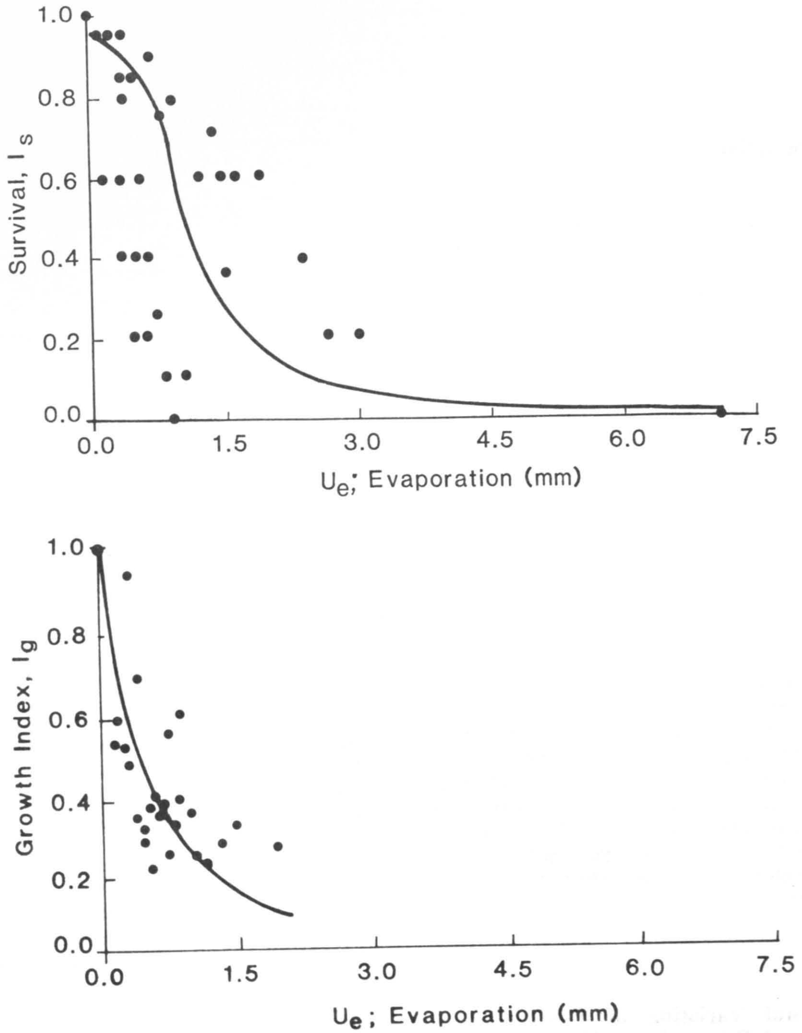

Figure 4.12. Survival (*top*) and Growth Index (*below*) of plants as a function of evaporation, U_e.

5. SUMMARY

Introduction

Considerable resources are used nationally and internationally for tree planting programs. Forest regeneration inventories indicate that not all the transplants survive to produce marketable timber. An additional productivity decline is due to the decreased growth of the survivors. Experts assume that much of the damage, especially with barerooted transplants, is generated when tranfering the plants from the nursery into the field. The reasons for the damage are, however, hard to determine. Plants do not develop visible symptoms until several weeks after the mistreatment. The plant injury is thus a gradual process rather than an instantaneous event. Both environmental stress factors and plant physiological factors are involved. Information regarding the injurious processes is needed so as to mitigate the damage and to decrase the costs of the tree planting programs.

The main objective of this study is to develop concepts and methods for recognizing and analysing the dynamic aspects of injury development in tree transplants. An additional objective is to apply the new methods to empirical data in order to make a contribution to the information regarding the relative importance of selected factors affecting the damage.

Temporal Variation of Environmental Factors: A Comparison of Transportation Bags

Scots pine transplants were placed into different transportation bags and the environmental factors inside the bags were monitored in field conditions. The transplants were planted after a one-week exposure and were examined at the end of the first growing season.

Temperatures up to +50 °C were recorded inside the bags. The temperature inside the bags were found to vary more rapidly than that of the ambient air. The evaporation rate was relatively high, especially inside partially transparent bags. Plants stored in the upper part of such bags were damaged during storage whereas plants in other kinds of bags, or in the lower part of the transparent bags escaped damage. It was concluded that substantial temporal variation existed in the environment affecting the plants. This variation needs to be considered when selecting methods for analysing plant damage. A method which would meet this requirement is presented in Section 3.

Response of the Plant: the Dynamic Injury Model

Injury is defined in this study as a decrease in either survival or growth. Following the concepts of Levitt (1972), strain is defined as the physiological pathway through which the injury develops. Stress is defined as any *environmental* factor affecting the strain. Stress resistance is the corresponding plant *internal* factor involved.

Plant injury tends to develop slowly. The death of a plant, for example, is often the termination point of a long process of deterioration. Stress in turn, as was shown by conditions inside the bags, varies rapidly. These differences create serious difficulties for the direct use of statistical bioassays, i.e. to determine dose-response functions where stress is the dose and injury is the response. A solution to these difficulties is proposed as described below:

The concept of strain is separated into i) a rate variable concept and ii) a state variable concept. The rate variable concept, strain rate, can be related to the fast variables and the state variable concept, accumulated strain, can be related to the slow variables. Accumulated strain is defined as the time integral of the strain rate. Through this link a bridge is built between the fast "dose" and the slow "response". Statistical bioassays can be used in order to relate the accumulated strain to the injury.

Manifestation of the Injury: Expriments for Ranking Selected Factors

Several hypotheses were tested regarding injury to barerooted Scots pine plants. Unprotected plants were subjected to stress conditions before planting. Measurable variables, such as evaporation demand, solar irradiance and temperature were used so as to quantify the stress. Both stress resistance and the planting site were standardized, and this made it possible to calculate the accumulated strain based on the stress variable only. The calculated strain was related to the injury – that is the decrease in survival or growth – measured after two growing seasons. In one experiment the stress resistance of the roots was compared to that of the plant shoot by protecting either the roots or the shoot and then letting the plants dry out.

In the above mentioned experiments the transplants were planted on homogenous nursery sites. The effect of a larger variability in the planting site was tested in the next experiments. Plants were subjected to a standard stress and were then planted on different sites in order to study the joint effect of accumulated strain and planting site.

The results indicated that plants are particularly sensitive to the desiccation of the roots. Direct stress of solar radiation in terms of, for example, UV-radiation was found insignificant. Plants were relatively tolerant to vibration and dropping. High temperature induced severe plant injury beyond an abrupt threshold around +50 °C. The same proportional injury due to a standard desiccation treatment was observed over a wide range of planting sites.

This study indicates that it is not fruitful to describe plant injury as a function of stress in a static way. A method is developed which takes into account the dynamic features of the injury development. The method, the Dynamic Injury Model, can be used for effective comparisons between the injury and the potential triggering factors.

The empirical results together with similar findings in the literature provide the basis for recommendations with regard to the implementation of tree planting programs. The main focus should be on controlling root desiccation. This could best be done with indirect methods because evapotranspiration is difficult to monitor in the field. Basic physical laws confirm that high evapotranspiration rate is frequently associated with high temperature. Controlling high temperatures thus serves as a means of controlling root desiccation.

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Total of 94 references

Appendix 1. Background information of experimental conditions and plants which all were raised on open nursery field two years before and one year after the transplantation. Plants were thus of the type 2+1.

Section of report	Focus of Experiment	Number of plants	Origin of seed				Nursery			
			Location	Latitude	Longitude	Code	Location	Latitude	Longitude	Lifting date
2.3.5.	Bag env.	360	Kalvola	61°06'	24°07'	T3-68-7	Hietikko	60°56'	22°40'	May 10, 1978
4.2.1.	Str. duration	320	Tervo	62°57'	26°45'	T10-69-51/453	Suonenjoki	62°39'	27°03'	June 1, 1977
4.2.2.	Evap. stress	320	Tervo	62°57'	26°45'	T10-69-51/453	Suonenjoki	62°39'	27°03'	June 1, 1977
4.2.3.	Solar stress	360	Tervo	62°57'	26°45'	T10-69-51/453	Suonenjoki	62°39'	27°03'	June 1, 1977
4.2.4.	High temp. str.	220	Tervo	62°57'	26°45'	T10-69-51/453	Suonenjoki	62°39'	27°03'	May 15, 1977; May 24, 1977
4.2.5.	Vibration	180	Tervo	62°57'	26°45'	T10-69-51/453	Suonenjoki	62°39'	27°03'	May 15, 1977
4.2.5.	Dropping	360	Kalvola	61°06'	24°07'	T3-68-7	Hietikko	60°56'	22°40'	May 10, 1978
4.2.6.	Shoot vs. root	180	Somerniemi	60°34'	23°44'	T3-69-48	Hietikko	60°56'	22°40'	May 4, 1979
4.2.7.	Site grad.	600	Kalvola	61°06'	24°07'	T3-68-7	Hietikko	60°56'	22°40'	May 10, 1978
4.2.8.	Misc. sites	1000	Somerniemi	60°34'	23°44'	T3-69-48	Hietikko	60°56'	22°40'	May 4, 1979

Section of report	Duration of transport from lifting to storage, hours	Duration of Storage in bags at 2°C, days		Date of experimental treatment	Location of planting site		Watering at planting	Date of injury measurement	Effective temperature sum, degree days after planting	
		before experimental treatment	between treatment and planting		Latitude	Longitude			First growing season	Second growing season
2.3.5.	5	A:35; B:23	0	June 2-21, 1978	61° 50′	24° 15′	yes	Sept. 13-20, 1978	A:860; B:750	-
4.2.1.	1	2-7	0	June 3-12, 1977	62° 39′	27° 03′	yes	Sept. 25-28, 1978	860-840	1120
4.2.2.	1	2-7	0	June 3-12, 1977	62° 39′	27° 03′	yes	Sept. 25-28, 1978	860-840	1120
4.2.3.	1	13	0	June 14, 1977	62° 39′	27° 03′	yes	Sept. 25-28, 1978	820	1120
4.2.4.	1; 1	1; 2	2; 2	May 16, 1977; May 25, 1977	62° 39′	27° 03′	yes	Sept. 25-28, 1978	970;950	1120
4.2.5., v.	1	1	2	May 16, 1977	62° 39′	27° 03′	yes	Sept. 25-28, 1978	970	1120
4.2.5., d.	5	32	2	June 13, 1978	61° 50′	24° 15′	yes	Sept. 13-14, 1978	770	-
4.2.6.	5	25	0	May 29-June 4, 1979	61° 50′	24° 15′	yes	Sept. 15-16, 1980	1020	1170
4.2.7.	5	16-17	3	May 26-27, 1978	61° 50′	24° 15′	no	Sept. 14-15, 1979	960	1180
4.2.8.	5	20-29	1-5	May 24-June 2, 1979	61° 50′	24° 15′	no	Sept. 15-16, 1980	1020	1170

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Author's address: Department of Forest Economics, The Finnish Forest Research Institute, Unionink. 40 A, SF-00170 Helsinki 17, Finland.

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