Adapting Existing Forests to Climate Change

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- «Ecological Engineering for Effluent Recycling through Intensive Silviculture»
- «The Interaction Between Climate Change, Soil Moisture Stress and Stand Density in a Red Pine Plantation»
- «Climate Change Mitigation. Are there any Forestry Options?»
- «Software for Effluent Recycling through Intensive Silviculture»

Abstract

Increasing levels of greenhouse gases, GHGs, in atmosphere are at the root of increased global temperatures, also termed global climate change. Using sophisticated general circulation models, GCMs, until recently, predictions were consistent in documenting that a doubling of atmospheric CO_2 concentration will likely result in an increase of 3 ± 1.5 °C, globally, probably before the end of 21st century (Houghton 1977). However, a recent IPCC report (IPCC 2001) affirms that the warming will be in the range of 1.4 to 5.8 °C. Associated with climate warming are increased variability and more frequent extreme phenomena, droughts and floods. Ecosystems, in general, will have difficulties adapting to this fast pace of change. Due to their longevity, forests are likely to suffer severe hydric stress during extended dry episodes.
The paper shows that already in the 20th century in central North America (Ontario and Michigan) sizable warming was clearly evident in standard weather records and was accompanied by a corresponding increase in precipitation.

In search for practical means to adapt existing forests to the ecological challenges of warmer weather, especially to accrued potential evapotranspiration, ETp, this paper examines the effect of stand density reduction on soil water regime. Through continuous soil moisture measurements in a mature stand of red pine, accomplished with time-domain reflectometry equipment, TDR, in various treatments of a thinning experiment, the soil moisture regime was found to react strongly to stand density manipulation. It is inferred that in order to avoid hydric stresses that might become acute, even deadly in dense stands, due to increased weather variability, forests will have to be thinned more often in the future. At the same time, the beneficial effect of density reduction on the growth of individual trees is demonstrated through diameter increment measurements. With stand density reduction, the diameter increment of thinned stands increases, revealing a good potential for shortening the rotations.

Summing up, considering the large area of existing Canadian forest, the paper argues for the idea that a common and long known silvicultural practice, thinning, when periodically applied, shows a real possibility to achieve (1) increased ecological stability of stands, through lessened accuteness of anticipated summer water deficits, (2) shorter rotations, and (3) larger diameter stems. These consequences will accelerate the opportunity for renewal of existing stands with species better adapted to the shifting of ecological conditions.

Keywords: climate change, silviculture, thinning, soil moisture regime.

Contents

▲ 1. Introduction

At the beginning of the Third Millennium we live in an era of increased environmental awareness, in which governments and various international agencies have became aware of several major challenges, such as: population increase, poverty and climate change. Among these, climate change is perhaps the most insidious and least localized. It began very slowly, concomitant with industrial revolution and associated increased energy use, which opened up major pools of fossil fuels, lying underground sealed from contact with the atmosphere. Release of chemical potential energy of these pools occurred with massive emission of some optically active gases, such as carbon dioxide (CO_2) and nitrogen oxides (NO_x), initially considered benign. To these, other gases with similar properties, such as methane (CH_4) and nitrous oxide (N_2O), were added resulting, respectively, from anaerobic decomposition of organic matter and biomass burning. Modern additions to these gases are tropospheric ozone (O_3) and chlorofluorocarbons (CFCs).

In short, these gases are optically active because they allow the penetration of the incoming solar radiation (short wave) while trapping the outgoing caloric radiation (long wave), thus generating atmospheric warming, which compounds from one year to the next.

The immensity of globe's atmosphere and the active mixing of gases, initially, prevented this effect from being apparent. Only when the effects of the warming process became sizable, in the late 1940s, a scientific rationalization was sought (Bolin et al. 1986). In fact, an explanation has been provided at the end of 19th century, when the Swedish scientist Arrhenius re-examined available measurements related to absorption of terrestrial radiation in the atmosphere (Bengtson 1994). At that time, Arrhenius correctly determined the role of CO_2 and water vapour, and was able to quantify the change in surface temperature resulting from an increase or a decrease in atmospheric CO_2 concentration. Based on preliminary data for surface albedo and cloud distribution, Arrhenius calculated that a doubling of CO_2 concentration, from 300 parts per million of volume, ppmv, to 600 ppmv, would result in about a 5 °C warming, a result comparable to what is accepted today (Houghton 1997). However, Arrhenius did not link the man-made CO_2 release to warming, since at that time the amount of fossil coal used was still small, about 0.5 bil. tons annually. Today, with an over 20-fold increase in the burning of fossil fuels, the situation has changed radically (Bengtson 1994).

The prospect of global climatic change, known also as "the greenhouse effect," is now seriously considered by several international and national fora around the world. The driving force of warming, thoroughly reviewed by Houghton (1997), is the increasing atmospheric concentration of optically active gases. By the mid 21st century, in the absence of mitigative action, atmospheric CO_2 levels are likely to double from their pre-industrial level of 270 parts per million to about 540 ppmv, reaching about 700 ppmv by 2075.

Contemporary modeling of the warming process, which is still developing, asserts that for a doubling of CO_2 concentration, at temperate latitudes, we can expect an increase of 3 ± 1.5 °C (Houghton 1997). At end of the 20th century, in central Ontario, increases of temperature and precipitation of 0.76 °C and 5-7%, respectively, were already evident in standard meteorological records (Papadopol 2000). Globally, the warmest years this century were 1998, followed by 1987 (Jones et al. 1998). The global climate change is believed to cause increased disturbances: unmatching between climate and traditionally existing vegetation formations, forest fires, insect and disease outbreaks, windstorms and regional drought and flooding (Weber and Flannigan 1997). These influences appear to be even more threatening since the publication of a new IPCC report (IPCC 2001) revised the rate of warming, placing it up to 5.8 °C up to the end of the 21th century.

Although general circulation models, GCMs, have increased in sophistication in the last three decades, hand-in-hand with revolutionary progress in computing technology on which they depend, still GCMs cannot predict regional details of future climates. From an ecological viewpoint, the warming scenarios given by GCMs are alarming, and have the potential to significantly destabilize the major ecosystems. Apart of the magnitude of the warming, an additional prediction of all models is that, along a meridian, the warming will be progressively greater at higher latitudes and during winter (Dixon et al. 1994; Kirschbaum and Fishlin 1996, Easterling et al. 2000).

Considering that the global mean temperature was probably only 2 - 5 °C below present temperature at the time of the maximum extent of continental ice masses in the northern hemisphere, 20 000 - 15 000 years ago (Hansen et al. 1984; Overpeck et al. 1991), a recorded ~1 °C increase in global temperature over a century represents a more rapid change than has ever occurred in the post-glacial period (Cannell et al. 1989). If this trend continues, the thermal climate of central Ontario might soon become similar to what we know traditionally for Nebraska or Iowa, with ensuing dramatic changes in vegetative cover and reduction of forested areas (Houghton 1997). Canada, with its transcontinental band of boreal forest and its northerly position is very interested in these predictions and their potential for global destabilization effects. With an area of boreal forest of 315 x 10^6 ha, occupying 75% of all forested land, the potential effects of the warming on the ecological stability of currently exploitable forest are enormous (Canadian Council of Forest Ministers 1997; Kuusela 1992).

Compared to agricultural crops, trees appear as biological entities able to stand a larger variability of ecological conditions. However, the major forest types require a stable climate to exist and reproduce. If we consider a common rotation lasting close to a century, recently established forests will end up growing in an environment warmer by at least 3 - 5 °C. A large, and growing, body of scientific literature asserts that, from the ecological standpoint, they might not be able to stand a change of this magnitude in such a short interval. However, for practical reasons, renewal of these forests with species adapted to warmer climates will have to wait for the end of current rotation. Since increased temperature brings with increased climatic variability (Glantz and Wigley 1987; Smith et al. 1998), and more extreme weather events (Wigley 1985; Francis and Hengeveld 1998; Easterling et al. 2000), forest managers will have the additional task to organize the structure of forests to withstand future stresses without growth reductions or other risks. At the same time, they have to consider that with warming the whole environment changes. While existing forests are immobile and, possibly, in declining vigor, some disturbances, such as insect pest and diseases, are expected to increase their virulence with the warming trend (Fleming and Volney 1995 ; Lindroth et al. 1993; O´Neill 1994; Volney 1996).

Since the atmospheric demand for evapotranspiration will increase with a warmer climate, conceivably, the hydric stress experienced by dense forest stands will accentuate during the more frequent summer dry episodes, with corresponding reduction of increment. To maintain the current growth rhythm and vigor, necessarily, the existing forests will require greater amounts of water from the sites on which they grow. It is therefore imaginable that the stand density control could reduce the per tree hydric stress and increase ecological stability of stands. Moreover, if the CO_2 emissions were to be held at current levels, due to atmosphere's inertia, the increase in concentration of GHGs will still continue for at least two to three centuries (Watson et al. 1996). Therefore the climate change effects are likely to continue, with their ensuing ecological consequences, for a long time. Consequently, effective adaptation strategies have to be devised for the maintenance and active growth of stands already established, for a wide range of forest ecosystems.

When proper consideration is given to the link between climate, stand density and soil water regime, prudence demands careful attention to be paid to scientific foundation and to simplicity and operational effectiveness of means selected to secure, year after year, sufficient soil available water from a more variable precipitation regime. The balance of this paper will attempt to (1) assess physical changes occurring in the forest environment, with an emphasis on soil water regime, (2) evaluate thinning as a means to improve growing season soil moisture balance, and (3) monitor the increment of residual trees following stand density reduction.

▲ 2. Scope and methods

With this research, an attempt was made to examine the potential of thinning as a means to help existing forests adapt to climate change. Red pine was selected for this research since it is widely planted in Ontario and Michigan, and is one of the species on which future intensive silviculture developments with conifers will likely be based. Finally, stands of red pine are frequently established on sandy sites that have only a limited water storage capacity and are prone to episodic severe water deficits (Rudolf 1950; Horton and Bedell 1960).

To define the local trends, it was considered useful to examine the evolution of temperature, T, and precipitation, P, in the last century on a "transect" across central Ontario and the Lower Michigan Peninsula, based on existing records summarized in Boden et al. (1994).

The field work was organized in a red pine plantation (*Pinus resinosa* Ait.), established in 1927, with 3-year-old seedlings, in Kirkwood forest, 90 km East of Sault Ste. Marie, Ontario, Canada (46°14' N. Lat., 83°26' W. Long.). The plantation is situated on a deep sand deposit, with groundwater inaccessible to forest vegetation. The density reduction treatments were: heavily thinned, HT, moderately thinned, MT, and lightly thinned, LT, plus an unthinned control, UC, in four replications of each treatment. At end of 1992 a complete inventory was made, allowing for the determination of stand density, expressed as basal area per hectare. At that time, the average stand basal area was 41.04, 44.35, 47.31 and 62.98 m^2 ha^{-1}, respectively, in HT, MT, LT and UC.

A very large clearing near the trial was instrumented with a weather station recording air temperature, air relative humidity, global solar radiation, and wind speed. Rainfall was measured with 8 rain gauges. The sensors were connected to a 21X Campbell Scientific micrologger, programmed to take a scan every 10 seconds and to log a record every 10 minutes. Subsequently, the air saturation deficit and the Penman standard ETp were calculated (Jensen 1983).

The soil water regime was monitored in one replication of each treatment by means of TDR. In every monitored replication, three profiles (subsamples) of 7 probes, with sensors placed horizontally at 8, 16, 24, 35, 60, 90 and 120 cm, measured hourly the soil moisture. The sensors were connected through coaxial cables and a multiplexer to the micrologger. The sensors (three parallel rods of stainless steel of 0.3 m assembled solidly in a mount), multiplexers and microloggers compose the Trase-1 soil moisture system, manufactured by Soil Moisture Co., California, U. S. A. Once a week, data were downloaded from the micrologger, the subsamples were averaged by strata and the soil water content was calculated in each treatment for the 150 cm soil profile.

Four soil samples were collected from each depth of TDR sensors to diagnose the wilting point, WP, determined with sunflower (Jensen 1983). Based on these values, the inaccessible soil water content in mm of water was calculated for the stratum of soil represented by each sensor and summed for layer 1 (0 - 30 cm), layer 2 (31 - 150 cm) and total soil profile (0 - 150 cm). For the local sand, the water equivalent of WP was 80.29 mm.

From the soil moisture content, the volume of water stored in the profile to a depth of 150 cm was determined using the methodology described by Ratliff et al. (1983). Then, the available water was determined as the difference between the amount of water in the profile at hourly intervals and the water held in profile at WP.

In order to gauge trees´ reaction to density reduction, in each treatment, 30 trees were equipped with dendrometer tapes which were read weekly during the growing seasons of 1993 - 1995 to 0.01 mm. Subsequently, the soil available water and the weekly tree increment were graphed on the same time scale.

▲ 3. Forecasted climate change and some ensuing effects

Evolution of CO_2 concentrations during the last 160,000 years has been determined in cores of fossil ice sampled from Vostok, Antarctica (Chappellaz et al. 1990). It appears that at the end of the last glaciation, the CO_2 concentration increased to a pre-industrial value of 270 ppmv, then remained practically unchanged until the beginning of the industrial age, around 1750. Subsequently, CO_2 concentration increased exponentially, currently amounting to 360 ppmv (Boden et al. 1994).

Climate is an extremely complex ensemble of physical, chemical and biological processes, interacting at all levels in the atmosphere and the oceans. The main components that constitute the climate system are exchanges of energy (heat in various forms) and momentum (wind stress and turbulence) that occur within these media and between them. In climate modelling, the major scientific problems involve the intrinsic complexity and the widely different time scales, complicating the coupling of processes (Houghton 1977). For these reasons, atmospheric models are so very computationally demanding.

Currently, atmospheric models provide long-term (100 years) simulations for various hypotheses of CO_2 concentration. In one of these scenarios, called scenario A (business as usual), the Intergovernmental Panel on Climate Change, IPCC, assumed that CO_2 emission will continue to grow at the rate of slightly more than 1% annually, or an exponential increase. Conversely, in scenario D, a drastic CO_2 reduction with stabilization around year 2025 is assumed (Bengtsson 1994). However, presently, the annual CO_2 increment is 1.6 ppmv year,$^{-1}$ based on a 10-year average (Keeling and Whorf 1994). The importance of simulation efforts is that the scenarios appear sensitive both to human interventions (e.g. deforestation and GHGs emissions), as well as to seasonal photosynthetic activity (Boden et al. 1994) and these influences are quantified through successive approximations.

When the seasonal evolution of atmospheric CO_2 concentration is analyzed, great differences appear due to geographic position and vegetation cover. Compared in Fig. 1 are two sites with long monthly CO_2 determinations: Mauna Loa, USA and Mount Cimone, Italy (Keeling and Whorf 1994; Colombo and Santaguida 1994). Firstly, it is evident that a seasonal pattern exists. Secondly, due to seasonal opposition of climate in the Northern

Hemisphere (with large forested areas) versus the Southern Hemisphere (with large ocean covered areas), the curve for Mauna Loa at (19° 32' N. Lat.) is somewhat flat, although it still reflects the seasonal pattern of Northern Hemisphere. In contrast, data from Mount Cimone at (44° 11' N. Lat.) reflect the strong seasonal pattern of temperate forest vegetation (**Figure 1a**), with a depression of CO_2 concentration from May to October. The annual average values of CO_2 concentration, provided for the two localities exhibits a striking similarity (**Figure 1b**). Examination of the two graphs point to two main consequences: (i) forests play a great role in climate stability at global scale, and (ii) the ascending trend of atmospheric CO_2 concentration is already very steep. Additional CO_2 concentration data, provided by Boden et al. (1994) for different points in the world, lead to similar conclusions.

Climate has also a major direct influence on vegetative cover through the frequency and severity of disturbances by fire, insects, extreme weather, and hydrologic regimes (Overpeck et al. 1990). Under similar climate, various ecosystems have different water consumptive uses, depending on species, albedo, season and structure. For example, the actual ET of *Pinus radiata* forests in the Southeastern Australia is likely to be some 30% higher than that of irrigated grassland on an annual basis (Cromer 1980). As a result of unsatisfied moisture demand, drought stress is a common phenomenon, and most likely will increase in the future, potentially reducing the amount of merchantable timber produced. Occurrence of dead trees, dead tops and heavy needle cast observed in *Pinus resinosa* plantations over most of central Ontario and Michigan is worst after dry years, and in dense, unthinned plantations, or on shallow soils (Rudolf 1950; Horton and Bedell 1960).

In general, the GCMs used for predicting future climate (Lau et al. 1996; Bengtsson 1994; Boer et al. 1992, McFarlane et al. 1992, are designed for two hypotheses: present day (1 x CO_2) and doubled (2 x CO_2) CO_2 scenarios, roughly corresponding to atmospheric CO_2 concentration in the fourth quarter of 20th century and those contemplated for the mid-21st century, respectively. In central Canada and USA, temperature is projected to increase 2 - 4 °C by the year 2030 (Karl et al. 1991). Such rapid change will likely lead to important modifications of ETp, soil moisture availability and growing season duration. It is interesting to note that the trends predicted by models are already apparent in the standard weather observations (Boden et al. 1994; Papadopol 2000).

However, more important appears the fact that forest adaptations, in terms of species´ ranges, will have to be made within only one to two generations (Burns and Honkala, 1990). Examining other predicted ecological influences, several authors emphasized changes of forest productivity, successional patterns, and, especially, shifts in geographical ranges of species (Andrasko 1990; Botkin et al., 1989; Davis, 1989; Gates, 1990; Overpeck et al., 1991; Solomon and Bartlein, 1992). Summing up, since under severe moisture stress cell division in the cambium ceases (Shepherd 1964), most often manifested as a result of drought imposed during the summer and autumn (Jackson et al. 1975), we might expect this to be the process that will lead to forest decline. Conversely, Stogsdill et al. (1992) found that stand density reduction increased the amount of soil available water in thinned stands. As a result, the "per tree" basal area growth of residual trees increased significantly. In other words, the direct effect of temperature is dangerous especially because it increases the atmospheric demand for evapotranspiration. If this happens when water is also scarce, it can result in a widespread forest decline and even loss of forested area (Gates, 1990).

In central North America, the impacts of climate warming are expected to be more noticeable at the fringe of the southern boreal, composed of mixtures of long-lived species (Jones et al. 1994). Consequences of environmental changes could result not only in growth decline, but also in the disruption of reproduction mechanisms, thus gravely affecting the ecosystem stability and diversity. Perhaps the biggest climate change-related concern is that of extreme weather events, which have increased in frequency in the latter half of the 20th century (Francis and Hengeveld 1998; Easterling et al. 2000). Increasing suddenly the energy exchanges, these events appear to affect especially the hydrological cycle through severe droughts or floods.

When considering the impacts of climate change on forests, attention must be given to all its consequences, not just to the physical effects of temperature increase. Of particular importance for ecosystems has the increase of ETp, especially during the dry spells that normally appear during the growing season. Considering that - with the exception of northeastern Ontario - the majority of forests in Ontario and Michigan are established on glacial till or sandy deposits, that drain quicky after a rain event, these forests will be the first to experience growth declines as a result of increased drought frequency (Millers et al. 1989, LeBlanc and Foster 1992, Reed and Desanker 1992).

Another disturbance strongly related to climate and soil moisture regime is wildfire. Weber and Flannigan (1997) assert that, in terms of area, in Canada this disturbance had an almost exponential growth in the last 70 years, while Parker et al. (2000) show that it represents an average loss of about 200 000 ha forest year,$^{-1}$ in Ontario alone.

Among other disturbances related to climate change is the warming of forest soils, with its direct consequence: accelerated decomposition of organic matter, itself an exponential function of temperature (Nichols 1998). This will affect the extensive areas of peat in northern Ontario, causing additional release of CO_2 and methane. A warmer atmosphere, fostering increased soil aeration, will reduce the storage of organic matter, potentially with positive implications for forest productivity. Existing growth models valid for boreal forests suggest that climatic warming will increase the productivity of forests in areas where soil water is not limiting, while the productivity will decrease where water becomes more scarce (Cannell and Dewar 1995; Cannell et al. 1998; Kellomaki and Karjalainen 1996; Kellomaki et al. 1997; Pastor and Post 1988). In Ontario, Canada, these two contrasting situations exist in Northeastern Ontario, where the clay belt maintains a high groundwater level, and Northwestern Ontario, where the permeable soils drastically reduce the water availability, which, judged through the amount of rainfall, should otherwise be sufficient.

The normal effect of increasing temperature is a rise of atmospheric demand for evaporation, leading to episodic hydric stress. This has already been suggested as an explanation for regional declines of several tree species (Millers et al. 1989). Perhaps some of the species most sensitive to climate warming are the birches, as has been noted in northern Michigan by Gates (1990) and Jones et al. (1992), following repeated dry episodes between 1987 and 1989. In an exploratory study, Jarvis (1986) used the Penman-Monteith model to determine the hydrological consequences of climate modification, finding radical changes of vegetation on a regional scale.

Moreover, Cannell et al.(1988) have shown that, as the temperature rises, and, with it, the saturation vapor pressure deficit, water use by forests increases considerably. The inevitable consequence of this direct, physical effect is higher ETp in a more climatically variable environment. Therefore, the existing forest will experience increasingly debilitating hydric stresses, followed by reduction of growth vigor and, possibly, dieback, unless, through density control, the consumptive water use per tree can be maintained at pre-warming levels.

▲ 4. Historic trends of climatic parameters

Since the GCMs do not yet offer regional predictions, T and P trends were analyzed along the central Ontario-Lower Michigan Peninsula transect. Annual averages of T are presented in **Figure 2**, **Figure 3**, while the P sums, are given in **Figure 4** for Ontario and Michigan.

Temperature trends are particularly important because they are at the origin of population migrations (Peters 1990; Pitelka 1997). When annual T averages are compared, the Ontario and Michigan values match almost perfectly, indicating that the evolution of air temperature was governed by large scale atmospheric systems. The departures from local averages vary, roughly, between 0.5 and 1 °C, with the multi-annual trend being clearly ascending. In the case of the P sums, local influences are known to result in more variability of rainfall events. In about one century, the P sum has increased by about 100 mm, representing about 12%. A prime consequence is that, with global warming, the same amount of water is recycled faster, which might result in a more active atmosphere. In a similar, but more restricted, analysis in Ontario, positive trends were also illustrated by the long-term records of T and P (Papadopol 2000). These results are consistent with the increases presented by Dixon et al. (1994), for the same geographical region. As the patterns of air circulation change in the future, regional forecasting will, probably, gain in importance.

▲ 5. Evolution of available soil water

Soil water content in the thinning treatments differed considerably, with the HT always having the greatest moisture content and the UC the lowest; soil moisture in MT was always closer but inferior to HT, while it was always superior to LT. This ranking is a clear illustration of the influence of stand density on actual evapotranspiration, ETa, with the densest stand resulting in the highest soil water depletion.

To describe the differences between treatments and the influence of rainfall on soil water content, the months of June - August, corresponding to the interval between day 152 and day 243, were selected in each year for a more detailed analysis. Precipitation sum for this interval amounted to 253.4 mm, 237.5 mm and 183.5 mm for 1993, 1994 and 1995, respectively. Since the daily ETa values cannot be determined this way, because drainage amount is unknown and could only be estimated through a soil water transport model (Hanks 1985), to get an idea of the evolution of atmospheric demand for evapotranspiration during the interval June - August of the three years, in **Table 1** the values of ETp for the same interval, calculated with the Penman model (Jensen 1983), are presented. The ETp for the interval June - August was almost identical over the three seasons.

Table 1. Rainfall and Penman ETp for June to August 1993, 1994 and 1995.

Year	Rainfall (mm)				ETp (mm)			
1993	number of events			34	avg.	.373 ± .017	ab. std.	.166
	total	253.40	max. event	30.25	total	342.87	daily max.	.708
1994	number of events			50	avg.	.379 ± .019	ab. std.	.181
	total	237.50	max. event	29.05	total	348.85	daily max.	.865
1995	number of events			37	avg.	.353 ± .015	ab. std.	.147
	total	183.50	max. event	35.70	total	324.98	daily max.	.710

The daily patterns of available soil water by treatment, for the 150 cm soil profile, in each of three years, are illustrated in **Figure 5a**, **Figure 6a** and **Figure 7a**. In general, the treatments evolved in a parallel manner, with HT consistently having the greatest proportion of available water in the profile. Water depletion during rainless episodes was most severe in layer 1 (0 - 30cm), especially in UC, where, at end of such intervals, less than 10% available water was left in profile (**Table 2**).

Table 2. Available water content at the beginning (day 208) and end (day 234) of a dry period in 1993, for four thinning treatments.

Stratum		Heavy Thinning (mm)	Moderate Thinning (mm)	Light Thinning (mm)	Unthinned Control (mm)
Layer 0 - 30cm	begin	31.14	25.44	21.36	14.04
	end	13.64	9.78	6.80	1.82
Layer 31 - 150cm	begin	135.50	116.00	102.10	77.10
	end	87.20	72.50	62.20	43.65
Profile 0 - 150cm	begin	164.64	141.44	123.46	91.14
	end	100.84	82.28	69.00	45.47

An additional effect of density is apparent each summer on the curves showing the pattern of available water in UC. During severe dry episodes, it can be noted that the decrease of available water accentuates more sharply in UC, compared with the other treatments. The highest percentages of available soil water occurred immediately after rainfall events, while the lowest ones were attained after periods of severe stress. During a dry episode, between day 208 and day 234 in 1993, the soil water content and the available water fell markedly in all treatments. Comparing the amount of available soil water in HT in layer 1 at the beginning of the dry episode (31.14 mm) and the end (13.64 mm) a reduction of 56.10%

occurred. In contrast, in layer 1 of UC only 14.04 mm of available water were found at the beginning, and just 1.82 mm at the end, exhibiting a reduction of 87.04%. A similar, but milder, effect was apparent in layer 2, from 35.65 to 43.39% for treatments HT and UC respectively (Table 2). The more pronounced reduction in layer 1 is, most likely, due to the superficial rooting habit of red pine.

Throughout the same dry episode, soil saturation with accessible water, in the first layer was 33.45% in HT and only 6.83% in UC (**Table 3**). It is conceivable that, in a longer dry episode, to be expected under a more variable weather (Easterling et al. 2000), the soil water availability in a dense stand may decrease to nil for a number of days, leading to severe, possibly, irreversible stress.

Table 3. Saturation with accessible water at the beginning (day 208) and end (day 234) of a dry period in 1993.

Stratum		Heavy Thinning (%)	Moderate Thinning (%)	Light Thinning (%)	Unthinned Control (%)
Layer 0 - 30cm	begin	55.63	50.60	46.23	36.11
	end	35.45	28.25	21.49	6.83
Layer 31 - 150cm	begin	70.96	67.66	64.80	58.17
	end	61.13	56.66	52.87	44.05
Profile 0 - 150cm	begin	67.48	63.79	60.59	53.16
	end	55.67	50.61	46.22	36.16

▲ 6. Weekly diameter increment

The weekly circumference increment measurements with dendrometer tape provided valuable information both on the effect of thinning and the relation between hydric stress and diameter increment. **Figure 5b**, **Figure 6b** and **Figure 7b** present the current diameter increment during the growing seasons of 1993, 1994 and 1995.

In the first two years of the study, in general, the diameter increment in MT was slightly superior to that in HT. The implication is that, initially, a too drastic opening of the stand may slightly depress the growth. In the third year, probably due to crown development, for which there was more space in HT plots, this situation was reversed. An intriguing case is presented by LT. The current diameter increment for this treatment is consistently closer to MT and HT than to UC. Implied is that any density reduction, has a positive impact on diameter increment, thus confirming the results of Zahner and Whitmore (1960).

In what regards the influence of dry episodes on the weekly increment, they exist and are important, but are somewhat obscured by the irregular timing of the rain events. Rains, suddenly increasing the amount of available soil water, interrupt an interval with depressed increment, a fact obvious from the parallel representation of the amount of available water and current diameter increment (Fig. 5, 6 and 7), thus confirming the results of Jackson et al. (1975).

▲ 7. Thinning as a means to adapt the forests to climate change

As the water consumptive use of the forest increases with age and crown development, the equilibrium existing between forest type and climate became more precarious. From tree increment measurements, it is clearly apparent that the greatest influence on growth and vigor is exerted by the soil water availability, which decreases with increasing stand density. However, in the future, this effect will be compounded by increased climatic variability, resulting in a certain "fragility" of the ecosystem. For example, in a year drier than 1995, in a dense stand, the atmospheric demand for evaporation may decrease the soil saturation with available water up to nil, which, if prolonged, may result a depression of stand vigor, and, possibly, in stand's death.

At this point in time, to take care of this circumstance, which worsens by the year, only one realistic silvicultural intervention in the life of stand can be advocated to reverse this trend. Thinning of the stand can strongly modify soil water use per tree, thus maintaining the high diameter and volume growth rates (Whitehead et al. 1984) and, possibly, shortening the rotation. Although the stand volume of residual trees will slightly decrease (Cooper 1983, Dewar and Cannell 1992), the residual trees will grow in a more "ecologically-secure" environment, with less risks from climatic variability. This is one of the "no regrets" options that are worth pursuing independently of climate warming concerns (Rubin et al. 1992).

At the same time, thinning is advantageous because the timber volume is redistributed to fewer individuals, thus increasing their value and probability to be used in long-lived products (which increase their carbon sink function) and detracts them from energy use (that speeds up their carbon recycling function). In no case, in the new scenario of climate warming, with an increased occurrence and severity of droughts, will a modern forest manager tolerate the self thinning of naturally regenerated stands through mortality induced by competition, as was too often the case in the past. The corollary is that, in aiming at increased ecological stability of existing stands, we should accept the idea that thinning will have an increased role in the future silviculture. This might be helped considerably by the fact that climate change will lead, gradually, to the renewal of existing forests, with an increased proportion of forests, planted with genetically selected material.

▲ 8. Discussion

This research has shown the influence of stand density on the water use of red pine stands of varying densities. Also, it provided direct evidence that soil moisture is depleted faster in a denser stand. These findings corroborate with the results of Cregg et al. (1990) and Stogsdill et al. (1992) who found that stand density exerts a major influence on the water use of loblolly pine. Due to combined effects of actual ET and drainage, in a typical dry episode, the amount of available water in the soil of UC plots, the densest treatment, fell to a dangerously low value, 1.5 mm in the first layer (**Table 2**), with the water uptake being greatest from the upper soil layer of UC. Therefore, during a growing season, a red pine stand maintained at high density will increase its water consumption close to maximum available water on a sandy site, with ensuing growth reduction consequences. In this scenario, a stand can be easily thrown of balance even owing to "normal" climatic variability. However, should this variability increase, as appeared to be the case during the 20th century, this risk might grow significantly.

Comparison of percentage of available soil water among treatments showed that water uptake by red pine was consistently from the top soil layer, consistent with its rooting pattern. In other words, during an intense rain event when soil moisture increases beyond the root zone, the water is lost gravitationally from the soil water reservoir explored by roots and percolates to groundwater. This situation is more extreme on permeable soils and for shallow rooted species. Conversely, on loamy soils, the fraction of water that percolates to the groundwater is reduced. Its residence time, elevated due to texture, increases its availability especially for deeply rooted species, which can satisfy a greater proportion of their consumptive use from deeper strata. Obviously, this process may make soil water balances determined by simple bookkeeping procedures appear more optimistic than reality, because drainage is, usually, inaccurately accounted for, or even ignored.

A prime consequence of an improved water supply is higher and less variable diameter increment. This corroborates with the findings of Cregg et al. (1988). But, apart from the effect on increment, other important ecological implications are also evident. The fact that water supply is affected by stand density is critical not only for the growth of trees. It is even more important for the survival of the stand.

In the context of increasing climatic variability (Bolin 1986; Houghton 1997), the positive influence exerted by the stand density control over available water is, perhaps, the only tool available for adapting existing forest to cope with future stresses. Because the influence of an intervention gradually diminishes over time, a policy of increasing the periodicity of interventions might be beneficial in the future. Reduction of stand density, which also decreases the demand for water, as demonstrated here, is especially important in monocultures, where competition for this primary resource occurs at the same level in soil, thus confirming the results of Whitehead et al. (1984).

It is therefore necessary that more information about the soil water uptake rates of various species and stand structures be obtained. Especially important, for the success of future efforts to increase carbon sequestration through intensive silviculture, is the understanding of relation between stand structure and physiological parameters. This can be achieved only through careful experimentation in characteristic stands. From this standpoint, sandy soils, where high permeability accentuates the competition for water offer an important area of study. What would be required to elucidate the issue experimentally for various forest ecosystems and ages is a whole range of thinning trials combined with soil water monitoring. Certainly, the cost of such a research program might be important but the need of knowledge in this matter is great and urgent.

Finally, in the same climate change context, the study of soil water will most likely lead to a diversification of silvicultural solutions adopted for the vast expanses of permeable soils in Ontario. An immediate implication would be the promotion of some deeply rooted species, indigenous or exotic, in new areas. Such studies will be greatly helped by the validation of a comprehensive soil water transport model for forested sites, using on-site energy balance as input. Such a model would allow "exploration" of the water balance for species with various physiological traits, in areas where now only standard climatic parameters are known.

▲ 9. Conclusions

There is now widespread agreement in the scientific community that the increase in atmospheric CO_2 concentration is the cause of climate warming. For a scenario of 2 x CO_2, forecasted to happen in less than 50 years, the predicted increase in global temperature is at least 3 ± 1.5 °C, while up the end of the century we might have a warming of up to 5.8 °C. Weather records collected by standard meteorologic stations in the 20^{th} century show a clear increase in temperature amounting to between 0.5 and 1.0 °C in the last one hundred years, and an increase in annual precipitation of 8 to 12%.

In this new scenario, forest ecosystems are going to be faced with pressure for unprecedented environmental change, perhaps the most serious being a combination of increased atmospheric demand for evaporation combined with reduced available soil water, which may severely restrict their ability to grow and reproduce. These trends will happen on a background of increasing climatic variability. The role of silviculture in maintaining ecological stability will therefore increase. Thinning may be our only means to alleviate the negative influences, and risks, of a more variable climate.

Analysis of soil water regime under several stand density treatments revealed consequential differences in soil water availability in a mature red pine stand. During the growing season, soil moisture varied greatly due to rain regime, sometimes being down to values close to the wilting point, at end of dry spells. Subjected to similar water supply conditions, soil water content decreased as the stand density increased. At the two extremes, water was easily available in HT plots and scarce in UC plots.

Monitoring soil moisture with the TDR technique provided quality data and illustrated the wide range of variations of soil water availability. Results reported here show that the recording facilities offered by TDR equipment allowed for detailed studies of water availability, as the soil water reservoir is subject to rain, ETp and drainage. Also, these studies emphasise the suitability of this technique for investigating the effects of stand density on soil moisture. In future, analyses of these data, in conjunction with a soil water transport model, calibrated for the local saturated hydraulic conductivity, would provide valuable information about the soil water budget of forest soils and the percolation to groundwater.

Examination of tree increment reaction to stand density reduction has shown that as the individual trees have more space, their increment increases, but this increase remains sensitive to soil water availability. It stands to reason that, by periodically thinning the stand, a potential to shorten the rotation and to increase individual tree volume exists and should be taken advantage of.

In the context of the impending climate change, the topic of stand density influence on soil water availability remains primordial and deserves a thorough quantification. At this point in time, thinning remains the principal silvicultural means through which the forest manager can avoid severe hydric stresses and growth slowing, that are sure to be experienced as a result of increased climatic variability. To a certain extent, we can also use it to push a stand to rotation age during a time of marked environmental change. Hence, there is a need to research more this means, in order to better adapt it to the variety of species, ages and densities, and to use it more aggressively to increase the ecological stability of existing stands of various ages.

▲ Figures

- Seasonal variation of CO2 content
- Annual variation of CO2 content
- Temperature Departures - Northeastern Forests
- Temperature Departures - Great Lakes
- Precipitation - Northcentral USA
- Precipitation and available Water - 1993
- Precipitation and available Water - 1994
- Precipitation and available Water - 1995
- Current Diameter Increment - 1993
- Current Diameter Increment - 1994
- Current Diameter Increment - 1995

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