

**LITERATURE REVIEW: PHENOLOGY AND  
GROWTH OF BLACK SPRUCE AND ASSOCIATED  
COMPETITIVE VEGETATION IN RELATION  
TO THE TIMING OF AERIAL HERBICIDE  
APPLICATIONS IN THE CLAY BELT OF  
NORTHERN ONTARIO**

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**A Report under the  
Canada-Ontario Forest Resource Development Agreement  
Project No. 33027**

**March 1990**

The views, conclusions and recommendations are those of the author(s) and should not be construed as policy nor endorsement by the Ontario Ministry of Natural Resources nor Forestry Canada.

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CANADA ONTARIO FOREST RESOURCE DEVELOPMENT AGREEMENT  
PROJECT NUMBER 33027

LITERATURE REVIEW: PHENOLOGY AND GROWTH OF BLACK  
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## 1.0 INTRODUCTION

In the forest sector, herbicides are used to increase early crop survival and to maximize the growth and yield of plantations and natural stands of desirable species, mainly conifers, through the control of competing vegetation. The desired effect is to selectively suppress weed species, allowing desirable crop species to occupy dominant positions in the plant community, and hence, to effectively compete with surrounding vegetation for light, nutrients and soil moisture. Although there are relatively few long-term studies in Ontario that quantify the benefits of herbicide use in forestry, present information indicates that seedling survival and growth and yield are positively influenced by competition control (Russell 1988).

There are two main uses of herbicides in forestry, tending and site preparation. Site preparation with herbicides is conducted to control unwanted vegetation prior to establishing the new crop, while tending refers to the treatment of existing young plantations to promote crop establishment and growth, or the release of natural stands of desirable trees from competing vegetation.

Tending is generally recognized as an essential part of forest management in Northern Ontario. Aerial application of herbicides is the most common form of tending in use in Ontario. For example, in 1988, 64,071 hectares of land were treated with herbicides for tending purposes (Anon. 1988a). Currently, there are only two herbicides registered for aerial application in Ontario, 2,4-D and Vision (glyphosate). In contrast to tending, chemical site preparation represents only a small part of all site preparation activities in Ontario (approximately 3% in 1987) (ibid). Tending and site preparation programs that use herbicides require careful planning to ensure that the operations are completed safely and effectively.

Herbicide applications for tending purposes should ideally be conducted when the efficacy, or ability of the herbicide to produce its intended effect, is maximized. This usually occurs when target (or weed) species are most susceptible, and when the crop species is least susceptible to adverse effects of the herbicide. The total time available for effective herbicide applications is sometimes referred to as the 'spray window'.

An herbicide applicator must be able to reasonably predict the efficacy of a treatment before an operational program is feasible (Anon. 1985). Efficacy is determined by many factors, including the characteristics of the herbicide (mode of action, solubility, persistence, selectivity); application methods (application rate,

carrier, volume delivered, frequency of applications, timing of application in relation to climate and phenology); and the nature of the target (susceptibility, age specific susceptibility, density and degree of establishment, level of control desired, and the relationship between crop and target) (McCormack 1980), and the nature of the crop species (susceptibility in relation to phenology).

Several reviews (e.g. Richardson 1965; Haavisto 1967), have noted that there is little information available that correlates climate and other environmental factors with the developmental stages of black spruce (Picea mariana (Mill.) BSP) and its more common associates. Also, the physiological and biochemical processes underlying phenology, susceptibility and tolerance of conifers and the more common competing species are not well understood.

The ability to predict phenological development, susceptibility and tolerance of target and crop species over the course of a growing season would be of benefit to forest managers for planning aerial tending operations. This information is needed for the development of more detailed site and species specific prescriptions, including selection of herbicides, timing and frequency of applications and application rates. Cost saving measures such as a reduction in application rates during times when the target species are more susceptible, or the use of different application rates on different site types may prove to be feasible. Forest managers would also

benefit from the improved capacity for planning and scheduling spray operations.

However, before a definitive predictive model or site-specific prescriptions can be developed, an understanding of the basic interactions between phenology and the tolerance of both crop and target species is needed, so that spray windows can be better defined, on a species-specific basis. Also, variability in the development of target and crop species over time, and between different site types needs to be better defined, in order to assess risks of crop damage and/or ineffective weed control.

The purposes of this report are: i) to review the literature relevant to the phenology and tolerance of black spruce and its more common competitors in the Clay Belt of northern Ontario, in relation to aerial applications of the herbicides 2,4-D and glyphosate; ii) to identify gaps in the information base; and iii) to provide recommendations for further research.

## 2.0 TIMING OF AERIAL HERBICIDE APPLICATIONS

### 2.1 Properties of Approved Herbicides

#### 2,4-D

Common formulations of 2,4-D (2,4-dichlorophenoxy acetic acid) used for forestry purposes include Esteron 600, with the active ingredient present as a low volatile ester, and Formula 40F, with the active ingredient present as an amine salt. 2,4-D acts as a growth regulator, affecting respiration, food reserves, and cell division within the plant. Despite the fact that 2,4-D is the world's most studied herbicide, its primary mode of action is still not clearly understood (Anon. 1983).

The herbicide is readily absorbed through leaves or roots, and is translocated primarily in phloem with the sugars; it can also move with water in the xylem. Accumulation is primarily in young, rapidly growing meristematic regions of roots or shoots. Half life in the soil is usually not longer than 1 or 2 weeks during the growing season due to rapid decomposition by soil microorganisms (Anon. 1986a).

Sensitive weeds include most broadleaf weeds and brush, but differences in interception, penetration, translocation, metabolism and sensitivity of absorption sites leads to greater activity in broadleaf weeds compared to grasses. All weeds are more easily killed when growing rapidly in moist soil. The efficacy of 2,4-D in controlling raspberries, grasses and sedges is low (Anon.

1986a). In fact, use of 2,4-D may enhance the growth of raspberries on some sites (Anon. 1985).

2,4-D can be used for site preparation or conifer release treatments in forestry, and is usually applied using aircraft. Application rates for aerial application range from 2.4 to 4.8 kilograms of active ingredient per hectare. Choice of application rate depends on the species occupying the site and the treatment rationale. For example, maples and poplar may require higher rates to be effectively controlled. Site preparation treatments often require higher rates than conifer release treatments.

#### **GLYPHOSATE**

Vision is the trade name for the silvicultural formulation of glyphosate, or N-(phosphonomethyl) glycine. The active ingredient is present as a water soluble isopropylamine salt. Glyphosate is absorbed through foliage and translocated throughout the plant. The exact mode of action of glyphosate is not clearly understood, but it appears to inhibit amino acid synthesis and photosynthesis (Anon. 1983). Glyphosate is very immobile in the soil since it is rapidly adsorbed by soil particles. It is then rapidly and completely degraded in soil by microbial activity. Since this adsorption inactivates the herbicide, making it unavailable for root uptake, glyphosate provides no residual activity.

Compared to 2,4-D, glyphosate is a relatively non-selective

herbicide. Sensitive species include annual grasses; perennial weeds (quack grass, Canada thistle, field bindweed, milkweed, cattails, nutsedge, poison-ivy and strawberry); and brush (birch, poplar, raspberry, willow and maple). Conifers are tolerant but the basis has not been established. For most perennial weeds, applications are recommended at the pre-bloom stage of growth. For example, Canada thistle should be at least in early flower bud, milkweed at flower bud, and bindweed at full flower. Quack grass can be treated in the spring or fall when it is actively growing with at least four new leaves on each emerged shoot. For brush control, applications during periods of active growth are necessary. Limited effectiveness against certain shrubs, including speckled alder, has been noted (Anon. 1986a).

In Ontario, glyphosate can be applied by aircraft at rates from 1.1 to 2.1 kilograms active ingredient per hectare, depending on the species, prescription and desired result.

## 2.2 Considerations for Timing of Application

Herbicide applications should ideally be timed so as to maximize effects on target species and to minimize effects on crop species. This requires knowledge of the effects of the herbicide being used, in relation to phenology of the plant species being treated (Anon. 1985).

### 2,4-D

It is generally agreed that 2,4-D will harm all conifers when it is applied during their period of active growth (Schact and Hansen 1963). Black spruce and white spruce are relatively resistant to application of 2,4-D after their buds are fully set and the current year's growth is hardening. This is usually recognized by the presence of sharply pointed buds and an absence of lammas growth (Anon. 1984, Anon. 1986b). However, the Newfoundland Department of Forest Resources and Lands (Anon. 1985) notes that, since spruce crop species are more resistant, 2,4-D applications can be conducted during July and August with less reliance upon phenological differences for weed control than with glyphosate.

With 2,4-D, phytotoxic effects can be achieved after the target woody shrubs and hardwoods reach full flush and are actively growing, and prior to the onset of fall coloration (Anon. 1984, Anon. 1986b). In Ontario, maximum control is achieved in the period extending from the beginning of June to the third week in

July under normal weather conditions. On moister, more fertile sites or in the absence of drought conditions or cold weather, spraying can proceed until 2 to 3 weeks prior to the first occurrence of frost. Species that reproduce vegetatively by 'suckering', such as poplar and alder, may be only partially controlled in subsequent growing seasons (Anon. 1986b).

For spruce crops, tending with 2,4-D is generally conducted from mid to late July to maximize weed control and to minimize crop damage. The use of 2,4-D in site preparation usually involves the use of the low volatile ester form applied aerially immediately after the hardwoods reach full flush (Carruthers and Towill 1988). Site preparation with 2,4-D is possible from May until September although maximum control will normally be achieved in the period extending from the beginning of June to the third week in July.

**GLYPHOSATE**

A compilation of herbicide trial results from Nova Scotia showed that glyphosate application at release rates between late July and mid-September provided adequate control of woody species and raspberry for the subsequent 3 years (Anon. 1988b). In the Lake States the optimum control period for herbaceous species and grasses occurs in July or earlier (Anon. 1980). In the Maritimes, optimum control periods were similar but an even earlier treatment resulted in good initial control for one year (Anon. 1988b). Sutton (1984) indicated that applications of glyphosate in September, except at higher application rates (two kg a.i./ha and greater), generally showed reduced effectiveness for control of target species in Ontario. Glyphosate damage to conifers following mid-July release applications in the same season as planting have been documented for the Maritimes (Ingratta 1979).

For conifer release, glyphosate treatment is recommended only after conifers have developed a sharp bud and in the absence of lammass growth, after hardwoods reach full leaf, but prior to hardwood leaf coloration (Anon. 1984). The Vision label extends the spray window slightly to include some coloration of the target species, but not major leaf fall (Anon. 1987). The 1986 recommendations for control of mixed hardwoods, raspberry, alder and perennial grasses are similar (Anon. 1986b). Glyphosate application as a conifer release treatment should occur only at the stage of full leaf development of hardwoods and after the current year's growth of the spruce crop

has fully hardened, if crop damage is to be minimized (Gardener 1978; Anon. 1980; Sutton 1984). This occurs during the period from August to mid-September in Ontario under normal weather conditions.

Chemical site preparation standards provided on the original product label were to apply the herbicide after hardwoods reached full leaf, prior to the onset of fall coloration, or with some coloration of the target species but not major leaf fall (Anon. 1984). Consequently, the time available for glyphosate site preparation in Ontario is normally the period from mid-July to mid-September.

Several studies have confirmed damage to trees planted immediately after glyphosate site preparation (Vanden Born 1984). Vanden Born (ibid.) also notes that glyphosate application to a site in the same season as planting of conifers may injure newly planted seedlings, and concluded that a late summer application of glyphosate, using recommended site preparation rates, followed by planting the next spring would provide good control of target vegetation and crop safety. In Ontario, damage to current crop container black spruce has been observed following planting in the same season as glyphosate application (Carruthers and Towill 1988).

An advantage in applying glyphosate is that it possesses long term herbicidal and silvicultural efficacy with maximum control of target vegetation often occurring 2 years after application (Vanden

Born 1984). Sutton (1984) reported 95% control of aspen three years after glyphosate application on a well drained loamy soil. However, glyphosate does not provide residual control for grasses and other species that have already shed seed prior to the time of herbicide application (Anon. 1984; Anon. 1986b; Anon. 1987).

Occasional variability in glyphosate efficacy when applied to less vulnerable species has also been documented (Anon. 1980, Boyd et al. 1985). In the Lake States, it has been suggested that drought stress may have reduced glyphosate efficacy, and that the physiological condition of the target species could be more critical in determining glyphosate efficacy than it is with other herbicides. The current product label indicates that glyphosate should not be applied during drought conditions, and that rainfall within six hours after application or heavy frost may reduce the level of control (Anon. 1987).

### 2.3 Current Practices in the Clay Belt of Northern Ontario

In Ontario's Clay Belt, the rich clay soils on mineral soil upland sites tend to develop dense growths of grasses and sedges, raspberries (Rubus idaeus), woody shrubs (including mountain maple (Acer spicatum), beaked hazelnut (Corylus cornuta) and mountain ash (Sorbus decora)), and hardwoods (especially poplar) following harvesting. On peatland sites, the main competitors developing after harvesting include speckled alder (Alnus rugosa), willow (Salix spp.) and sedges (Carex spp.). Coniferous plantations established on these sites usually require tending to ensure adequate survival and growth of the new crop.

The extent to which these various competitors develop probably depends on the vegetation and forest cover present before harvesting, the site's nutrient status, and the degree of disturbance. Hence, gradients of vegetation develop on upland and peatland sites after harvest, depending on the original site types, that may require different tending prescriptions. Forest managers currently rely on site inspections to determine the need for herbicide treatment and the specific prescription to be employed. The framework provided by the Forest Ecosystem Classification system (Jones et al. 1983) developed for the Clay Belt provides an opportunity for research into vegetational succession following disturbance on different site types, and the development of improved predictive capacity for prescription making.

In the Clay Belt, 2,4-D is used mainly for conifer release treatments, for the control of susceptible woody shrubs on upland sites and the control of speckled alder on poorly drained sites and peatlands. Applications of 2,4-D for control of speckled alder on peatland sites are typically conducted from the third week of July to the first week of August, after the spruce crop trees have set bud and the alder is fully flushed and actively growing. Interest has been expressed by local industry in conducting release applications of 2,4-D for alder control in late May and early June, after the alder has flushed but while the black spruce crop trees are still dormant (Arnup 1985), but this has proven impractical due to the lack of weather conditions suitable for aerial applications and the inability to accurately predict phenological development early in the season due to high variability.

On upland sites, 2,4-D applications for conifer release are typically scheduled slightly earlier than for peatland sites, from the second week of July to early August, corresponding with faster development of the vegetation on these sites.

Upland sites characterized by weed species resistant to 2,4-D, such as raspberries and grasses, are usually treated with glyphosate for release of desirable spruce crops. Rich upland sites with severe competition are usually treated with glyphosate from early August to early September, corresponding to the period when the spruce

trees have hardened and set bud, and the target vegetation is actively growing. Application rates are determined by the manager according to the type and severity of the competing vegetation. Glyphosate is normally not used on peatlands since local experience has shown that speckled alder is only partially controlled by this herbicide.

Site preparation using both 2,4-D and glyphosate are also practised in the Clay Belt, often in conjunction with mechanical site preparation or prescribed burning. In these instances, herbicide applications are typically conducted in late June or July, after full leaf flush, followed by a late summer burn or mechanical site preparation in the fall, then tree planting in the following spring.

The precise timing of operational programs varies from year to year depending on phenological development of the vegetation, and the occurrence of weather conditions suitable for aerial application.

Herbicide applications for conifer release typically occur within a few years after a site has been planted and when weeds are still less than two metres tall. Release treatments are most effective if conducted before the crop trees have been suppressed (Vanden Born 1984). The frequency of application depends on the size and density of competition on the site and its rate of growth. On the most fertile sites in the Clay Belt, two applications of herbicide

are sometimes required to ensure release of the crop trees from competition. A typical prescription would be to apply herbicide in the second and fifth years following planting, although timing of the first application varies from one to three years following planting, and a second treatment is not necessary on some sites.

In the Clay Belt, a follow-up treatment to control sucker growth is often necessary on sites with a large component of poplar growth. On peatlands sites, speckled alder sometimes regenerates profusely by coppice growth from the base following treatment with 2,4-D, especially where the alder was particularly tall or dense, or treatment was conducted late in the season, necessitating a second application.

### 3.0 RELEVANT ASPECTS OF BLACK SPRUCE SILVICS AND PHENOLOGY

Black spruce occurs over a broad range of latitude, longitude, and local habitats and sites throughout North America. Throughout its natural range, it exhibits considerable chronological variation with regard to the onset and cessation of active annual growth as a result of changing macroclimate and topography.

For example, initial flowering commences about mid-May in the Lake States (Heinselman 1957), and in early June in northern Ontario (Millar 1936). In upper Michigan leaf bud opening averages June 6th (Heinselman 1957). In northern Ontario, the leaf buds begin to open about the first of June and are fully open two weeks later when the trees are in full flower (Millar 1936). In the Alberta foothills, Horton and Lees (1961) found that height growth commenced about June 1st, was greatest during the first two weeks of July, and was completed by August 2nd. At Cedar Lake, Ontario, (Latitude 50° 15' N), Belyea et al. (1951) found radial growth of black spruce started about June 1st, was half complete by July 10th, and was complete by September 3rd.

In addition to geographic variation, there is considerable variation in the time of flushing and height growth between local populations. This is partly the result of genetic variability and partly due to year-to-year climatic differences (Nienstaedt 1974). Fraser (1966) found the date of initiation of radial growth in

black spruce varied by about two weeks over a five-year period at Chalk River, Ontario.

Local topography and air currents can have great impact on local temperature variation, and as a result, tree species may show local adaptive variation to different sites (Nienstaedt 1975). This has been demonstrated in a study of bud flushing in Sitka spruce (Picea sitchensis (Bong.) Carr) conducted by Burley (1966). Several authors have reported genetic differentiation between upland and lowland populations of black spruce in Ontario. Cheliak and Pitel (1983) reported that lowland populations were consistently more variable genetically than their upland counterparts.

Jozsa et al. (1984) noted that black spruce has similar growth response to white spruce on well-drained soils, but not permafrost or bog habitats.

Black spruce exhibits free growth in the juvenile stage of its life cycle. The free growth phase gradually diminishes, and ceases between age five to ten years (Pollard and Logan 1975). After this phase, annual growth is determinate, originating solely from overwintered buds formed in the previous growing season. Pollard and Logan (ibid.) found strong correlations between latitude of origin and the amount of free growth in young black spruce seedlings. Hence, variation in height growth, and perhaps phenology, is most pronounced in young trees.

In white spruce, the time of flushing becomes progressively later as a tree ages. Up to a two week difference in the time of flushing between young seedlings and mature trees has been recorded for white spruce (Nienstaedt 1974).

Black spruce initiates growth later in the season than other conifers, usually flushing seven to ten days after white spruce throughout its range (LeBarron 1948). As a result, it is less susceptible to late spring frosts. This phenological characteristic is probably an adaptation enabling black spruce to successfully occupy the colder, wetter environments in peatlands (Vincent 1962).

Millar (1936) stated that black spruce is one of our hardiest conifers. Extremely cold weather has no serious effects, and frost cracks are very rarely found. Young growth, except for that growing under mature stands, can withstand most extremes of heat and cold.

#### 4.0 CLIMATIC INFLUENCES ON BLACK SPRUCE GROWTH AND PHENOLOGY

It has previously been noted that there is little information correlating climate with the phenology of black spruce in Ontario. This section will attempt to scope this problem by summarizing the literature available, including that from other jurisdictions and for other conifer species, and to identify those climatic factors likely to affect black spruce phenology, as a guide for future research.

Climatic factors are acknowledged to be the main environmental influences controlling the phenology of most tree species. Most authors agree that bud burst in black spruce is mainly controlled by temperature, while bud set and hardening are mainly influenced by photoperiod (Lavender 1988). Nonetheless, the relationship between phenology and climate is not completely explained by these factors, and many of the underlying processes controlling phenological response are not well understood.

The biochemical mechanism controlling changes in tree growth in response to environment is the production of growth regulators. These are believed to play a key role in the mediation and transmittance of climatic signals to the cambium (Balatinecz and Anderson 1989). Growth regulators influence not only the amount of apical and radial growth in trees, but also the form, structure, and distribution of developing tissues (Larson 1960, Zimmermann

1964). Physiological processes known to be influenced by growth regulators include cambial activity (including cell division and cambial dormancy), differentiation of cambial derivatives, cellular anatomy and dimensions, and the chemical composition as well as microfibrillar orientation in cell walls.

Growth potentials for black spruce are initiated by the formation of needle primordia in the buds at the latter part of the growing season. In black spruce, development of a large complement of needle primordia seems to depend on the ability to prolong needle initiation. The cause of curtailment of needle initiation is not known, but it could be one of the key parameters of intraspecific variation in growth of some conifers (Pollard 1973). Bud development is slower and of shorter duration at lower temperatures (Pollard and Logan 1977). Colombo et al. (1982) noted that needle primordia initiation in black spruce container stock ceased with the start of freezing temperatures in September. Since the timing of freezing temperatures in northern Ontario varies considerably from year to year, this could have a major influence on the subsequent year's growth. Phenological adaption of the apical meristem to deteriorating environmental conditions in fall can apparently influence growth potential in spruce.

Differences in seasonal weather trends may also influence growth potentials. In studies of bud flushing in Sitka spruce (Picea sitchensis (Bong.) Carr.) provenances on the U.S. west coast,

Burley (1966a; 1966b) noted that southern types in California continued to form needle primordia until December, whereas northern provenances in Washington stopped in October. This broad north-south trend varied locally depending on prevailing wind patterns. Logan (1971) reported that correlation between height growth and photosynthesis of jack pine (Pinus banksiana Lamb.) could only be found in fall. Ledig (1969) has suggested that trends in assimilation are linked with phenological events in the bud. Colombo et al. (1982) noted that seedling size in black spruce appeared to influence the number of needle primordia formed.

Although black spruce exhibits variability in the timing of phenological events from year to year, few authors have documented this variability across Ontario. Year-to-year variation in phenology is important since height growth has been frequently correlated with the start, finish, rate, and duration of flushing, either negatively or positively, depending on species. Fraser (1966) found the date of initiation of radial growth in black spruce varied by about two weeks over a five-year period at Chalk River, Ontario. In a study of temperature requirements for bud flushing in white spruce clones, Nienstaedt (1974) found that the year to year difference between the earliest and latest average dates of flushing over four years of observations was about seven days. This difference equalled ten days to two weeks of degree day accumulation, and is shorter than the differences of 2 to 4 weeks reported for other species (Irgens-Moller 1957; Busgen and Munch

1929).

Growing season temperatures are important to plant growth and survival. Heat sums are correlated with the initiation of meiosis in vegetative buds of white spruce (Owens et al. 1977), the timing of bud burst and flowering in many species (Kazkurewicz and Fogg 1967), and with the progression of plant development from one stage to another, for example, the time required for seed maturity after flowering. In Michigan, northern range limits for some deciduous tree species parallel isopleths on heat sum maps (McCahn 1979). In Europe, cambial growth of trees has been correlated with mean July temperature (Mikola 1962), and in North America, a similar pattern has been found for conifers growing near the upper latitudinal and altitudinal limits of their ranges (Fritts 1976).

Soil temperatures may also have an influence on plant development although they are likely to be correlated with air temperatures on upland sites. Heinselman (1961) checked soil temperatures in Michigan at a 6-inch depth and found that black spruce bud burst occurred when the soil was still between 38° and 46° F. Both shoot elongation and radial increment were well advanced before 6-inch soil temperatures reached 50° F, for the entire range of sites he examined.

Temperature has also been related to growth, biomass production, and wood formation in forest trees. Mikola (1962) reported several

temperature-growth relationships for trees growing at northern latitudes in Fennoscandia. In northern Finland, radial growth was found to be largely associated with mean temperature. High latewood percentages were associated with longer growing seasons, as well as with high July temperatures. For current biomass production of Scots pine, the temperature of the previous summer was the most important factor. However, needle length was primarily influenced by prevailing temperatures during their actual growth. Jozsa et al. (1984) noted that the degree of correlation of temperature with tree ring widths is generally greater than corresponding values for precipitation.

The pattern of accumulation of heat over the growing season may also influence phenology. In Nienstaedt's (1974) study of white spruce bud flushing, the lowest degree day requirement was recorded in the year with the coolest spring, and the latest recorded date for flushing. His field observations were confirmed by studies in the greenhouse; there the lowest degree day requirements were also recorded in the coolest environment. He notes that "the verification of these observations and the clarification of their physiological significance would be an important contribution".

There are other indications that the timing of warm temperature is important. White pine (Pinus strobus L.) growth has been correlated with late growing season temperatures of the previous year (MacHattie and Horton 1963). Thermoperiod is important for

the growth of some species, and thermoperiod requirements may vary depending on geographical location (Denton and Barnes 1987).

Winter temperatures may also have an important influence on tree growth. Strong correlations exist between winter minimum temperatures and the natural distributions of many tree species (Sakai and Weiser 1973; Bryson 1966). These limits have been associated with exotherms observed during experimental chilling of plant tissues (George et al. 1974). Both black spruce and white spruce have certain chilling requirements to assure prompt breaking of dormancy under greenhouse conditions (Nienstaedt 1966).

Temperature fluctuations are also important to the survival of trees in winter. Unseasonably warm air occurring when soils are frozen can result in drought injury to conifers (Curry and Church 1952). Maximum cold hardiness in trees is associated with dormancy plus extended exposure to cold. Rapid fluctuation in temperature is associated with frost damage, since warm periods can reduce the deep hardening of plant tissues induced by continuous cold temperatures, and injury to stem or bud tissues can occur when cold temperatures return (Weiser 1970). The combination of low extreme temperatures with high short-term temperature fluctuation may result in winter temperature regimes that are particularly rigorous.

Temperature variation in spring and fall may be equally damaging.

Late spring frosts may damage flowers, young shoots, and the cambium. Similarly, damage from early fall frosts can occur before hardening has progressed sufficiently to protect the plant.

Glerum and Paterson (1989) noted significant reductions in height growth resulting from spring frost damage in black spruce. Differences in site conditions in their study influenced the severity of frost and the extent of damage. Microscopic examination of tree rings revealed that frosts on the fresh sites were more severe than on the dry sites, although frost frequency was similar on both sites. This resulted in more terminal leaders and laterals of black spruce killed on the fresh site, causing greater loss of terminal dominance with considerable multiple-leadered "stem form" on the fresh site, while the single "stem form" prevailed on the dry site.

An adequate supply of water is important for tree growth. Water stress affects several aspects of tree growth (Zahner 1963, 1968; Kramer 1964). By its direct action, water stress might reduce cell division and cell enlargement. Indirectly, water stress can reduce photosynthesis, auxin synthesis, and the translocation of carbohydrates and auxins to the cambium.

Distribution of precipitation over the course of the growing season is also important. For example, lack of precipitation during the growing season can affect the current year's growth (Zahner 1968;

Downing and Weber 1984). Drought has been observed to interrupt shoot extension growth, and the growth of needles. Lack of late season precipitation may reduce fruiting and growth in the following year (Motley 1948; Zahner 1968).

The principal water balance variables are potential evapotranspiration and the ratio of midsummer precipitation to potential evapotranspiration (Denton and Barnes 1987). Evapotranspiration has been correlated with forest production (Rosenzweig 1968). However, this is probably less important in northern areas, which show much less difference between precipitation and potential evapotranspiration, especially in midsummer (Denton and Barnes 1987). Hence, significant effects on black spruce growth in the Clay Belt are likely to occur only under unusually severe drought conditions.

Black spruce has stomata that are very sensitive to atmospheric evaporative demands and plant water stress. Grossnickle and Blake (1985) postulate that this feature, in combination with less new root development over the first growing season, could result in planted seedlings that go into growth check because they can not maintain a moisture balance favourable for growth.

Winter precipitation may also be important to plant growth. Snow cover insulates the ground, and may reduce the possibility of freezing damage to roots, protect young seedlings (which are often

more sensitive to cold than mature trees) from freezing, protect roots from mechanical damage due to frost heaving, and protect seedlings from browsing herbivores (Denton and Barnes 1987).

Water table depths have been shown to influence black spruce growth. In a study of root and shoot growth of black spruce and larch, Lieffers and Rothwell (1986) demonstrated an important interaction between water table depths and soil temperatures. With both species and for all growth parameters, cool temperatures had a positive effect on trees grown in high water tables but a negative effect on trees grown at lower water tables.

Lieffers and Rothwell (ibid) postulate that cooling in the high water table treatments probably slowed bacterial respiration and, therefore, lessened the production of associated toxic products and the consumption of oxygen. At lower water tables, anaerobic conditions were probably not a major inhibitor of growth. Here low temperatures inhibited root development for both species; there was reduced root size and rooting depth compared with the control treatment. Other studies have shown that low temperatures can reduce root growth in forest trees (Soderstrom 1976; Tryon and Chapin 1983; Lopushinsky and Kaufmann 1984).

These findings have important implications for the growth and phenology of black spruce growing on peatland sites. They are especially relevant since approximately one half of black spruce

stands in the Clay Belt occur on peatlands (Ketcheson and Jeglum 1973). Peatlands are complex ecosystems that occur within climatically determined limits. Many of the soil conditions found in peatlands, including high water levels, poorly aerated soils, low soil temperatures, and frequently low levels of available nutrients, all of which limit tree growth, are climatically governed (Haavisto et al. 1989).

Peat soils are colder than upland mineral soils. In a study to monitor temperatures during the growing season in typical peat soils under a stand of black spruce near Cochrane, Ontario, Haavisto et al. (1989) observed that the peat layers near the surface were invariably warmer than those lower in the profile when measured at 1400 h, the warmest time of the day. Under the black spruce stand, the temperature at 30 cm rose steadily to about 11°C by the end of July. On July 29, only a 3°C difference occurred from the surface to a depth of 30 cm. The authors conclude that the growing season for roots may be rather short considering that near freezing temperatures were recorded just below the rooting zone in mid-June, and that temperatures in the upper part of the soil profile were already cooling by the end of July.

Photoperiod is thought to be the main factor controlling the timing of bud set and hardening off in black spruce. Observations of larch seedlings and the anatomical characteristics of their xylem by Balatinecz and Anderson (1989) confirmed that photoperiod plays

a decisive role in the regulation of extension growth and cambial activity. The authors noted that long days favoured continued shoot extension, while short days were associated with the cessation of extension growth, and the cessation of cambial activity despite optimal temperature and moisture regimes for growth provided during the experiment.

For greenhouse grown black spruce in northeastern Ontario, the critical daylength for timing of bud initiation is estimated at 14 to 15 hours (Colombo et al. 1982), which is reached at Swastika, Ontario between August 1 and 11. Needle initiation is almost 50% slower at temperatures of 10°C than at temperatures of 20°C or higher (Pollard and Logan 1977). Since temperature affects the rate of bud development, optimum conditions for bud development in the latter part of the growing season occur at warmer temperatures in the greenhouse, rather than outside (Colombo et al. 1982). Related studies of bud development under field conditions are not available for Ontario.

## 5.0 AERIAL SPRAY WINDOWS - PREDICTING PHENOLOGY OF CROP AND TARGET SPECIES

At present there is considerable uncertainty associated with planning aerial herbicide programs in Ontario's Clay Belt due to the relatively short and variable period that combines suitable weather conditions for aerial applications with the appropriate phenology of both the target and crop species. A better understanding of the relationships between phenology and herbicide tolerance, coupled with information about the silvical, physiological and environmental factors controlling phenology, would help the forest manager to better define spray windows and predict variability, and hence, to develop prescriptions on a site- and species-specific basis.

Parallels between the sciences of agriculture and forestry have often been drawn. Hence, agricultural research in this area may provide some direction. However, there are differences between agricultural and forestry practices that will likely create difficulties in transferring agricultural technology to forest ecosystems. Forest ecosystems, including young managed stands, are more complex and dynamic systems than most agricultural crop areas. The natural vegetation in these ecosystems are likely to exhibit more variability than agricultural crops, since they occupy a wide range of site conditions, are faced with more harsh and variable weather conditions in northern Ontario, and are more genetically diverse. The previous sections illustrated the complexity of

environmental influences on the phenology of black spruce. Given the likelihood of complex interactions between site, climate, silvics, and genetics, the task of modelling phenology of natural species on forest sites will not be an easy one.

In agriculture, many well-supported predictive models exist for a variety of crop and weed species, and different chemicals, which are useful for timing herbicide and pesticide applications. The most relevant agricultural research will be that for the culture of trees, that is, fruit tree management. For this purpose, several authors have shown that certain climatic variables, especially those related to temperature, such as cumulated degree-days, can be used to predict stages of phenological development in fruit trees (e.g. Anstey 1966; Harding et al. 1976). Various functions of temperature have been used to effectively model the phenology of other agricultural crops, including peas (Katz 1952), corn (Gilmore and Rogers 1958; Runge 1968) and wheat (Nuttonson 1955; Haun 1973).

The fruit tree models allow predictions of the expected dates of occurrence of the various phenological events at any point during the growing season. For example, Anstey's (1966) predictive model, developed for prediction of bloom dates of a variety of fruit trees in British Columbia and Nova Scotia, uses the following simple formula:

$$D = (T - A) / M$$

where: D = the predicted number of days from the current date until the event;  
 T = average number of degree-days to the event;  
 A = number of degree-days accumulated by the date of prediction;  
 M = average number of degree-days accumulated per day from the prediction date to the date of the event.

As the season progresses the predictions made by this model become more accurate. Mean errors for the prediction of fruit tree bloom dates ranged from +/- five days, 15 days after the start-date of heat accumulation, to +/- one day, 47 days after the start of heat accumulation. The model's accuracy varied with the tree species studied to a lesser extent.

Agricultural research points to the need for similar work in forestry. Long term observations of phenology are required for correlation with climatic variables. Most agricultural studies used ten to thirty years of crop observations to obtain reasonable accuracy. It is beneficial to understand the underlying physiological processes controlling growth and phenology of the species being studied. For example, the temperature at which growth is initiated, and hence, the baseline temperature from which heat units are summed for modelling growth, varies for different agricultural crop species. Also, different species respond to different climatic variables.

Long term observations of the phenology of black spruce and associated competing vegetation are not available for Ontario. A preliminary study at Kapuskasing developed a simple model of phenology of black spruce on both upland and lowland sites, and speckled alder on lowland sites, using the variable cumulated degree-days above 5 degrees Celsius. This variable seemed to show promise for predicting developmental stages of black spruce, although there was insufficient data for definitive testing. Preliminary data also suggested that development of black spruce on peatland sites lags behind that of black spruce on mineral soil upland sites (Arnup 1985). Peatland sites tend to be colder due to poor air drainage. Hence, one would expect the accumulation of degree-days to lag behind that on upland sites.

It appears likely that predictive models for the phenology of forest species can be developed. However, basic research into the physiological mechanisms underlying growth response to environmental factors, especially climate, is needed. Long-term observations of phenology on a variety of sites and in different geographic locations will be required to model spray windows across the province.

## 6.0 SUMMARY

A forest manager must make numerous decisions during planning of any aerial herbicide application program. These include selection of an appropriate herbicide, application rate, carrier, volume delivered, frequency of applications, and timing of the application in relation to climate and phenology. An applicator must be able to reasonably predict the efficacy of a herbicide treatment before an operational program is feasible. Information needed to predict herbicide efficacy includes the characteristics of the herbicide (mode of action, solubility, persistence, selectivity); the nature of the target (susceptibility, age specific susceptibility, density and degree of establishment, level of control desired, and the relationship between crop and target); and probable effects of the chosen prescription on the desirable crop trees.

Forest ecosystems, including young managed stands, are complex and dynamic systems. The natural vegetation in these ecosystems exhibit considerable variability, since they occupy a wide range of site conditions, are faced with harsh and variable weather conditions in northern Ontario, and are genetically diverse. This report reviews the complexity of environmental influences on the phenology of black spruce. Most authors agree that climatic factors are probably the dominant influences on phenology. Table 1 summarizes the documented effects of climate on the growth and phenology of black spruce and other conifers.

The ability to predict phenological development, susceptibility and tolerance of target and crop species over the course of a growing season would be of benefit to forest managers for planning aerial tending operations. This information is needed for the development of more detailed site and species specific prescriptions, including selection of herbicides, timing and frequency of applications and application rates. Cost saving measures such as reduction of application rates during times when the target species are more susceptible, or the use of different application rates on different site types may prove to be feasible. Forest managers would also benefit from improved planning and scheduling of spray operations. Given the likelihood of complex interactions between site, climate, silvics, and genetics, the task of modelling phenology of natural species on forest sites will not be an easy one.

In the author's opinion, the main gaps in the information base that require the attention of forest researchers are as follows:

1. Research into the basic physiological and biochemical processes underlying phenology, herbicide susceptibility and tolerance of black spruce and the more common competing vegetation species is needed.

**TABLE 1:** Summary of climatic variables and their documented effects on the growth and phenology of black spruce and other conifers. References listed in this tables are intended as examples; other documented sources exist.

<u>CLIMATIC VARIABLE</u>	<u>DOCUMENTED EFFECTS</u>
Temperature	Effects on diameter growth are greater than rainfall (Mikola 1962, Jozsa et al. 1984)
Freezing temperatures	Stops needle primordia formation (Columbo et al. 1984)
Heat sum	Correlated with initiation of cell division in buds, bud burst, flowering, and progression of developmental stages (Kaskurewicz and Fogg 1967)
July temperatures	Correlated with cambial growth (Mikola 1962, Fritts 1976)
Length of growing season (thermoperiod)	Correlated with extension of radial growth; minimum thermoperiod requirements determines range of many plant species (McCahn 1977)
Temperature of previous summer	Correlated with current biomass production (Mikola 1962)
Current summer temperatures	Correlated with needle length (Mikola 1962)
Cool spring temperatures	Reduces degree-day requirements for bud flushing in Sw (Pollard and Logan 1977)
Late growing season temperatures	Correlated with current year's growth (MacHattie and Horton 1963)
Winter temperatures	Minimum temperatures are correlated to distribution of many tree species (Bryson 1966; Sakai and Weiser 1973)
Winter temperature fluctuations	Can cause drought injury Can cause reduction in frost hardiness and frost injury (Curry and Church 1952; Weiser 1970)

TABLE 1: (continued).

<u>CLIMATIC VARIABLE</u>	<u>DOCUMENTED EFFECTS</u>
Late spring frost	Can cause damage to buds, flowers, and young shoots; delays in phenological development; reductions in growth (Glerum and Paterson 1989)
Early fall frost	Can cause bud and shoot damage if sufficient hardening has not yet occurred; reductions in growth next season
Growing season drought	Reductions in current year's growth; early cessation of active growth (Downing and Weber 1984)
Late season drought	Reduction of growth potential and flowering capacity for next season (Zahner 1968)
Photoperiod	Controls bud initiation; influences formation of needle primordia during bud formation (Pollard and Logan 1977)
Snow depth	Protection of young seedlings from frost damage, frost heave and herbivore damage (Denton and Barnes 1987)
Water table depth	High water tables reduce rooting volume; interacts with soil temperature to affect growth of both roots and tops (Lopushinsky and Kaufman 1984; Lieffers and Rothwell 1986)
Site factors	Microclimatic differences between sites, including frost frequency, heat sums, soil moisture have been shown to influence growth. This is mainly related to site position and aspect. Interactions between soil texture, structure and rainfall determine available soil water. Soil texture and water content affect soil temperature (Glerum and Paterson 1989)

2. Research into the relationships between phenology of both target and crop species and herbicide susceptibility and tolerance is needed.
3. Long term observations of phenology of conifers and main competing vegetation species in Ontario is required for modelling phenology in relation to climate and other environmental factors, and to enhance the ability to predict herbicide efficacy. Variability within local populations, between site types, at various locations across Ontario, and from year to year has not been adequately documented.
4. Microclimate in natural forest ecosystems and managed stands has not been extensively studied in Ontario. Microclimate may significantly influence the phenology and tolerance of vegetation. Many studies on climate in northern Ontario use data from established weather stations, which may not adequately reflect the conditions or variability on forested sites.
5. Successional trends of the vegetation on various site types following disturbances (including a variety of management practices) have not been well documented. This is needed to enhance our predictive capability for prescription making and planning.

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