BLACK SPRUCE SEED DISTRIBUTION WITH THE BROHM SEEDER/ PIPER PA-18A AIRCRAFT COMBINATION

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ABSTRACT

To achieve satisfactory seed distribution with the Brohm Seeder/Piper PA 18A aircraft combination, black spruce (*Picea mariana* [Mill.] B.S.P.) seed should be sown at 15-m inter-pass spacing and at auger speeds greater than 70 rpm. Black spruce seed is distributed across the swath in a bell-shaped pattern which peaks 1 m to the left of the aircraft track under calm conditions. At least 90% of the seed usually falls within a 15-m-wide swath under relatively calm conditions. Along the flight path, seed distribution occurs in a wave-like pattern that varies with auger speed (output rate); lower auger speeds produce greater relative wave amplitude and therefore increase variation in seed distribution. Acceptable deposit rates can be obtained consistently if calibration and sowing procedures are carefully followed. Steady winds of less than 10 km/hr do not have a major impact on distribution characteristics, but variable or shifting winds do. Deposit rates and distribution characteristics of 21 individual flights at three prescribed rates were analyzed, and the data were used to simulate the effects of inter-pass spacing and application rate on seed distribution.

RÉSUMÉ

Avec l'appareil Piper PA 18A et le Semoir Brohm, pour que la répartition des semences d'épinette noire (*Picea mariana* [Mill.] B.S.P.) soit satisfaisante, la distance entre chaque passage de l'aéronef devrait être de 15 m, et la vitesse du distributeur devrait être supérieure à 70 tr/min. Par temps calme, la distribution des semences sur le terrain a l'allure d'une cloche avec une pointe d'un mètre à gauche de la ligne de passage de l'avion. Au moins 90% des semences tombent ordinairement à l'intérieur d'une bande de 15 m de large lorsque les vents sont relativement calmes. Le long du trajet de l'avion, la répartition a l'allure d'une série de vagues qui varient en fonction de la vitesse du distributeur (débit); les vitesses plus faibles engendrent des vagues d'une amplitude plus grande, et, par conséquent, donnent lieu à une variation plus importante de la répartition des semences. Un dépôt satisfaisant et constant peut être obtenu si les méthodes d'étalonnage et d'ensemencement sont bien suivies. Des vents réguliers de moins de 10 km/h n'influent pas de façon importante sur la distribution des semences, mais il n'en est pas de même des vents variables ou changeants. Les dépôts et les caractéristiques de distribution observés lors de 21 essais différents pour trois débits ont été analysés, et les données ont été utilisées pour simuler les effets de la distance entre les passages et de la dose sur la distribution des semences.

ACKNOWLEDGMENTS

We wish to acknowledge the cooperation and assistance of General Airspray Ltd., and in particular K. Towers, D. Worgan and R.M. Hodgins. Forest research technicians J. Richenhaller and the late T. Silc assisted with the field trials, as did Silvico Forestry Services. We would also like to thank forest research technicians D.S. Mossa and M.J. Adams for preparing the figures; J.C. Edwards, R.F. Sutton and L.F. Riley for suggestions regarding the manuscript; Ontario Ministry of Natural Resources staff at Thunder Bay and Toronto for providing seed and administrative support; and E.F. Morningstar for typing the draft. Parts of this study were funded under a Canada-Ontario Forest Management Subsidiary Agreement research project for direct seeding of black spruce.

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Cover photo: Experimental layout.

INTRODUCTION

In Ontario, aerial seeding has been used as a regeneration technique since 1962. Initial development work in the province focused on black spruce *(Picea mariana* [Mill.] B.S.P.) and jack pine *(Pinus banksiana* Lamb.) but results with the former were discouraging (Scott 1966). As a result, while the area sown to jack pine has increased to over 20,000 ha annually (Smith 1984), aerial seeding of black spruce has for the most part been discontinued until the ecological requirements for successful establishment have been clarified (Scott 1968).

Lately, studies of seedbed receptivity, seed viability, seed treatments, shading, time of sowing, and seed predation (Winston 1975, Fraser 1976, 1980, 1981, Martell and Radvanyi 1977, Haavisto 1979, Jeglum 1979, 1981, Martell 1981) have renewed interest in sowing black spruce. However, seeding success is markedly influenced by deposit rates and distribution patterns as well as by biological factors (Régnière 1982)[2]. During recent trials, we found that aerial seeding procedures developed for jack pine (Worgan 1973, Foreman and Riley 1979) produced large variations in the distribution of black spruce seed. It was suspected that this resulted from aerodynamic differences between the seed of the two species. Consequently, we conducted a formal trial to refine procedures for sowing black spruce with the Brohm Seeder/Piper PA-18A aircraft combination.

MATERIALS AND METHODS

Aerial Seeding Equipment

The trials were carried out with the Piper PA-18A aircraft/Brohm Seeder combination. The PA-18A (the "Super Cub") is a light, high-wing monoplane, well suited to aerial seeding because of its fuel economy, dependability, 5-hour range and ability to operate from short (200 - 300 m) runways (Worgan 1973).

The Brohm Seeder, Mark III consists of a hopper from which the seed is fed by an auger to a revolving slinger beneath the fuselage, and is dispersed through four protruding horizontal plastic pipes. Both the auger and the slinger are electrically powered. The auger speed, which is monitored on a tachometer in the cockpit, can be varied to obtain the desired output rate. Slinger rotation is maintained at a constant 1000 rpm, regardless of output rate (Worgan 1973).

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[2] Where applicable, terminology follows that of the American Society of Agricultural Engineers (Anon. 1977). The term "deposit rate" refers to the actual number of seeds that land per unit area (seed/ha). "Distribution pattern" is the pattern of seed deposit on small, equal-sized units (e.g., 4 m^2 quadrats oriented perpendicular and/or parallel to the aircraft track) over the target area (Foreman and Riley 1979). "Application rate" refers to the calculated seeding rate (seed/ha) and is based upon the output rate and the area seeded per unit of time.

Procedures

The trials were conducted in April, 1982 on level to gently undulating farmland near Lucan, Ontario. Nine hundred numbered seed traps were arranged in a rectangular pattern of 15 parallel rows of 60 traps each (or, alternatively, 60 files of 15 traps each) (Fig. 1). Flight direction was perpendicular to the rows. Each trap consisted of a square wooden frame draped with fine polyester mesh, presenting a catch area of 0.27 m^2.

Aircraft ground speed was monitored with a hand-held radar, and flying height was determined with a Suunto clinometer. Wind speed and direction were recorded 1.5 m above ground in the middle of the seed trap array with an anemometer and wind vane.

Calibration procedures for the seeder were similar to those outlined by Foreman and Riley (1979) (Appendix). The seed lot used averaged 1106 ± 15.2 ($P = 0.05$)[3] seeds per gram. To ascertain auger precision, output rate was measured over a 30-second period eight times for each of seven auger speeds.

The same aircraft and seeding unit were used throughout the trials. Data were collected from 21 passes over the array: four at a prescribed output rate of 148 g/min, seven at both 296 g/min and 452 g/min, and three at an undetermined rate[4]. Flying height varied from 14.5 to 33.5 m, but most passes were flown at 20-25 m. Aircraft ground speed ranged from 113.5 to 148.5 km/hr and averaged 133.7 km/hr.

Under calm conditions, passes were made over the center of the array. When winds occurred with a sizeable vector perpendicular to flight direction, the aircraft track was shifted to windward to ensure that the seed fell within the array. Both the location of the flight path over the array and the number of seeds caught per trap were recorded for each pass.

Calculations

Seed catches were first determined for each row and file in the array for each flight. Then mean single-pass distribution patterns across the swath were calculated after the distributions across the swath had been aligned for individual flights so that their general shapes coincided. (Center lines of the distributions were superimposed.) Alignment was necessary because the location

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[3] Based on eight samples of 200-300 seeds each.

[4] The three stated output rates coincide with application rates of approximately 50,000, 95,000 and 145,000 seed/ha, respectively, at 1106 seeds/g, an aircraft ground speed of 138 km/hr and 15-m inter-pass spacing. The 'undetermined rate' resulted from inadvertent disruption of the tachometer setting before a series of three passes. Nevertheless, data from these three flights provide valuable information. Calibrated rates are reported in terms of output rates rather than application rates because output rate is the variable directly controlled by auger speed. Application rate is a function of aircraft speed, inter-pass spacing and the number of viable seeds/g, as well as output rate.

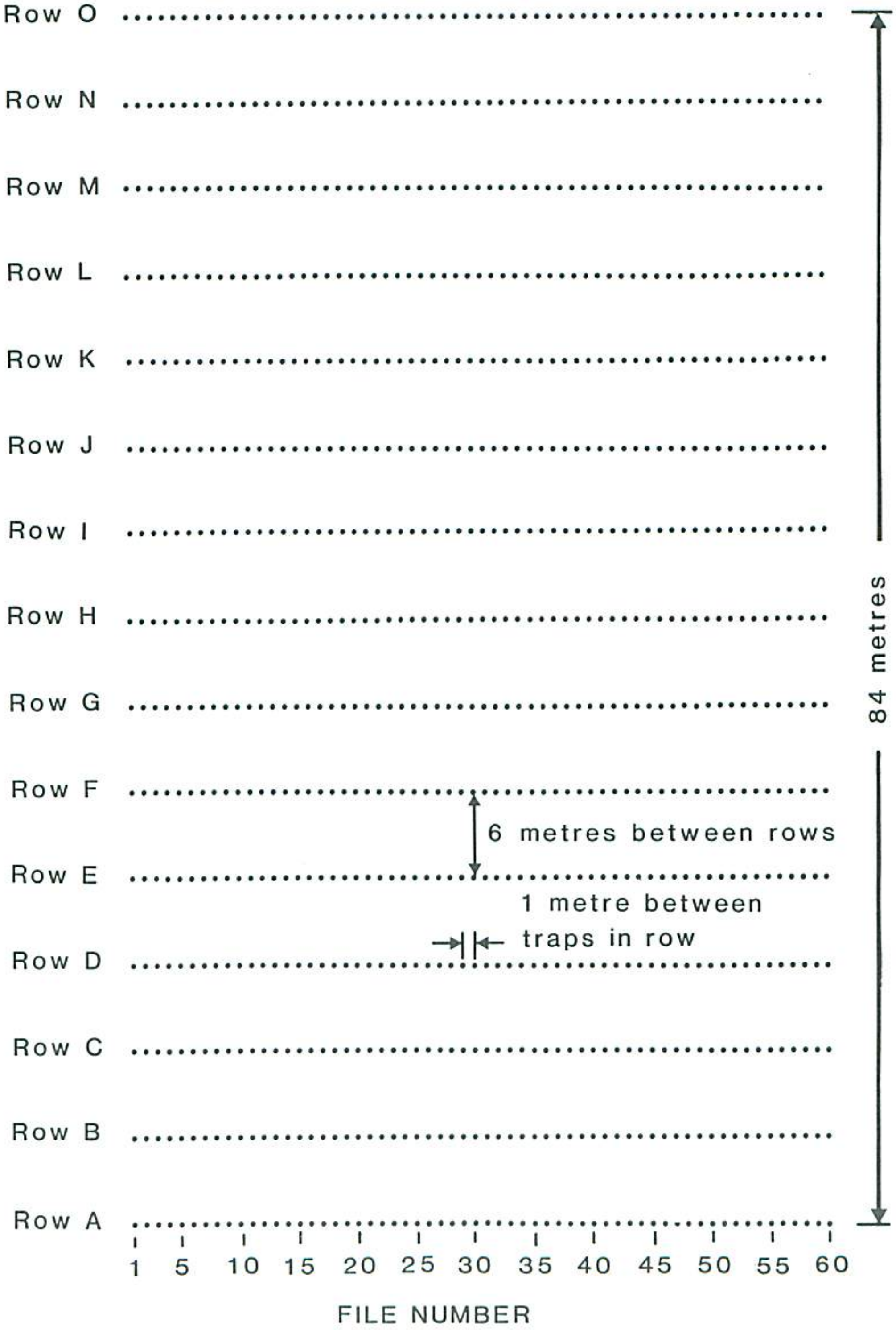

Figure 1. Seed trap layout

of the swath within the array varied from flight to flight, depending on the flying height, crosswind vector and the distance the aircraft track was offset to compensate for these factors. Patterns of seed distribution along the flight path were determined by examining seed catches on a row-by-row basis separately for each pass.

The distribution patterns across the swath and along the flight path were then used to generate expected[5] multiple-pass[6] distributions for three application rates at a variety of inter-pass spacings. Distributions were simulated over areas 1000 m wide by 2 m long, and output rates for each application rate were adjusted to accommodate the various inter-pass spacings. Variability along the flight path was taken into account by using a random starting point in this pattern for each simulated pass. The variance of the expected multiple-pass distributions was computed after standardization to mean = 1 (Régnière 1982).

Correlation and regression analyses were used to determine relationships ($P = 0.05$) between seed distribution characteristics and such factors as flying height, aircraft ground speed, wind speed and direction, and deposit rates.

RESULTS

Calibration of the Seeder

The calibration trials indicate that the seeder can be quickly and accurately calibrated to sow black spruce, regardless of application rate. There was little variation in output rate at any of the auger speeds tested. As well, the precision of output (as measured by the coefficient of variation) did not increase or decrease consistently with auger speed (Table 1). There was also a strong linear relationship between output rate and auger speed (Fig. 2), and this simplifies the calibration process. Once the output rate at any given auger speed has been determined for a seedlot, auger speeds needed to obtain different output rates with the same seedlot can be estimated easily.

Seed Deposition

Seed trap counts from each flight were used to analyze seed deposition as well as distribution characteristics. At higher output rates, mean deposits were close (88-102%) to those prescribed but, at the lowest output rate, the mean deposit was only 60% of that prescribed (Table 2). Likewise, the variation in deposit from flight to flight at a given rate declined as the mean deposit increased. In most cases, normalizing deposit to account for actual aircraft

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[5] The term "expected" refers to the results projected by simulation studies. Under field conditions distributions will vary somewhat, depending on such factors as wind conditions and variations in inter-pass spacing and aircraft speed.

[6] Adjacent swaths with alternating directions of flight.

Table 1. Relationship between auger speed and output rate[a].

Auger speed (rpm)	Mean output rate[b] (g/min)	Range in output rate (g/min)	Coefficient of variation
15	73.2	71.8 - 75.8	0.021
30	153.0	147.8 - 157.4	0.020
50	257.4	254.0 - 260.6	0.011
53	296.0	293.4 - 298.6	0.011
70	397.8	381.2 - 417.6	0.029
125	670.4	656.4 - 678.0	0.011
155	932.8	919.4 - 951.8	0.018

[a] Based on eight 30-second replications per auger setting.

[b] These output rates correspond to application rates of approximately 20,000 - 270,000 seeds/ha at 15-m inter-pass spacing, an aircraft ground speed of 140 km/hr, and 1106 seeds/g.

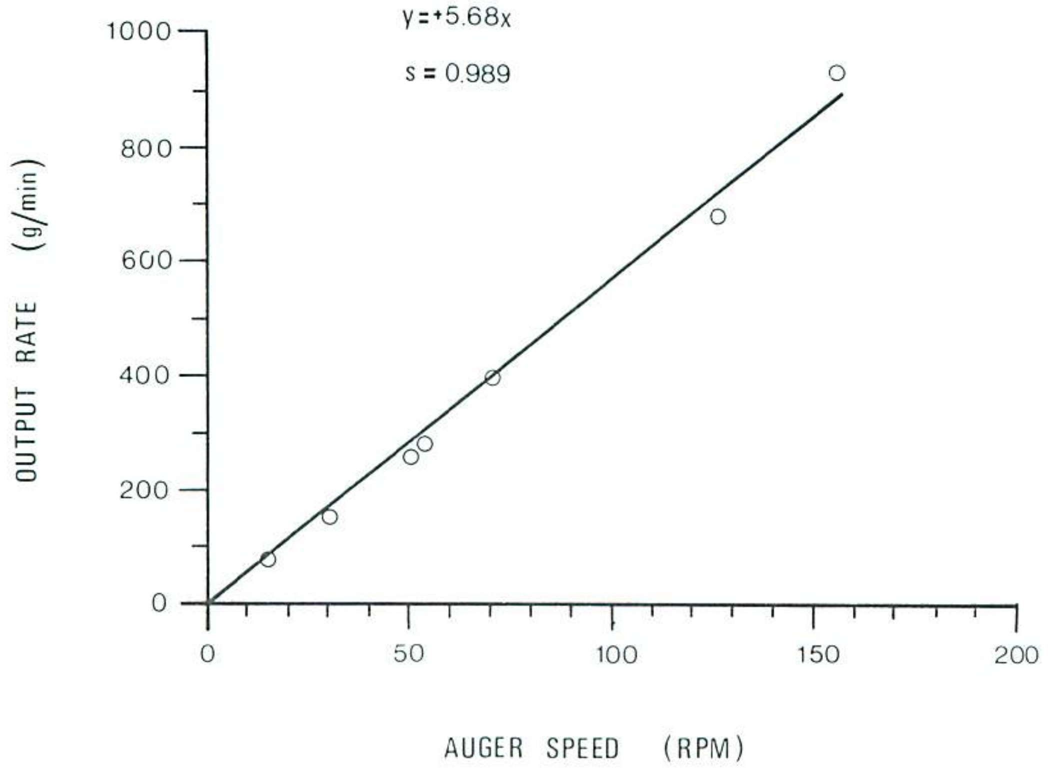

Figure 2. Relationship between output rate and auger speed.

Table 2. Seed deposition at different prescribed rates.

Prescribed output rate (g/min)	No. of flights	Mean deposit (g/min)	Proportion of prescribed output (%)	Standard deviation	Standard error	Coefficient of variation
148	4	83.1[a]	59	36.5	18.3	0.44
		83.6[b]	60	36.8	18.4	0.44
Unknown	3	172.4[a]	-	35.8	20.7	0.21
		165.3[b]	-	22.4	12.9	0.14
296	7	302.3[a]	102	38.5	14.5	0.13
		279.1[b]	94	29.4	11.1	0.11
452	7	398.5[a]	88	37.8	14.3	0.09
		397.8[b]	88	45.0	17.0	0.11

[a] Actual deposit.

[b] Normalized deposit.

ground speed[7] did not markedly alter mean deposits or reduce variation substantially. The combined variation associated with the estimates of seed weight (seeds/g) and output rate (g/min), as evidenced by the coefficient of variation for output in seeds per minute, accounted for approximately 5-30% of the variation associated with the mean deposits. Hence, most of the variation was a result of other factors.

Seed Distribution

Mean seed distributions across the swath were plotted for each of three deposit rates, corresponding to mean deposits of 83.1, 302.3 and 398.5 g/min (Table 2)[8], and for all flights combined (Fig. 3). The patterns were virtually identical and therefore the overall distribution pattern was used in subsequent analyses.

The effects of inter-pass spacing on expected seed distribution variance across the swath, following adjacent passes, are plotted in Figure 4. There is little variance at spacings up to 13 m but variance increases rapidly thereafter. The associated changes in expected seed distribution are illustrated in Figure 5. Differences become particularly pronounced as inter-pass spacing changes from 15 m to 20 m.

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[7] Normalized deposit = $\frac{\text{(actual deposit).(actual aircraft ground speed)}}{\text{prescribed aircraft ground speed}}$

[8] These in turn correspond to application rates of approximately 27,000, 97,000 and 128,000 seeds/ha, respectively, at 1106 seeds/g, 15-m inter-pass spacing and an aircaft ground speed of 138 km/hr.

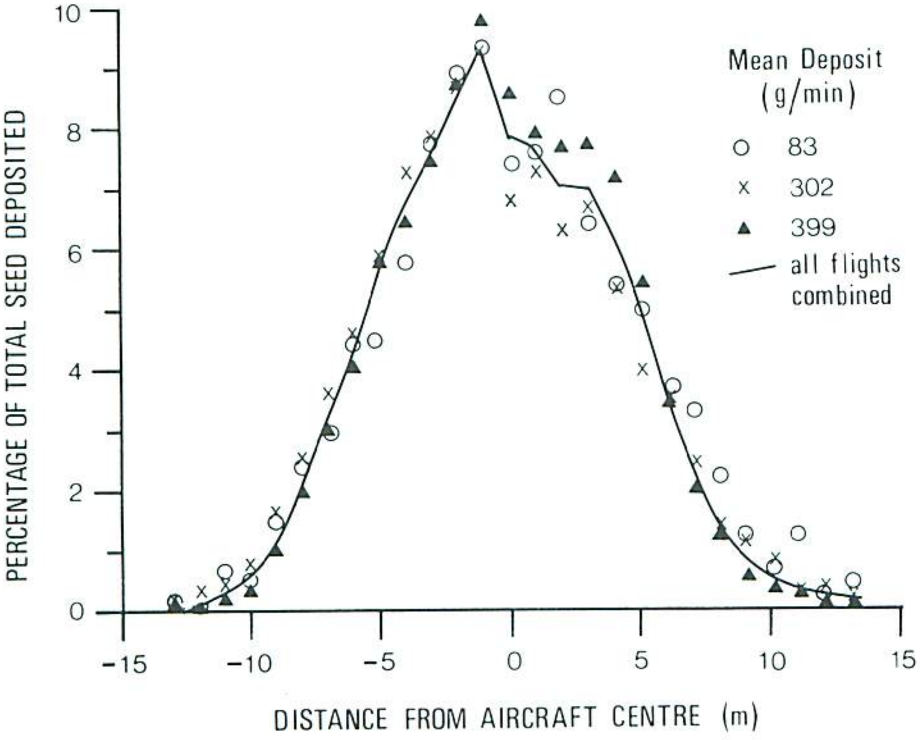

Figure 3. Seed distribution across the swath at three deposit rates.

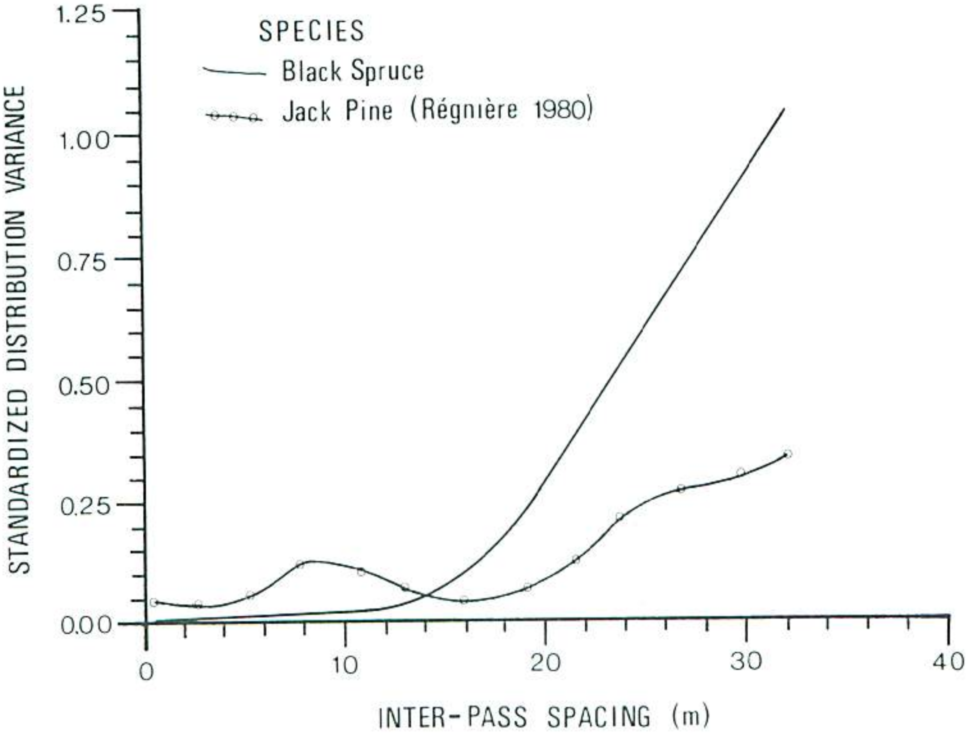

Figure 4. Variation in expected seed distribution across the swath, following multiple passes, as a function of inter-pass spacing (assuming no variation in distribution along each flight path).

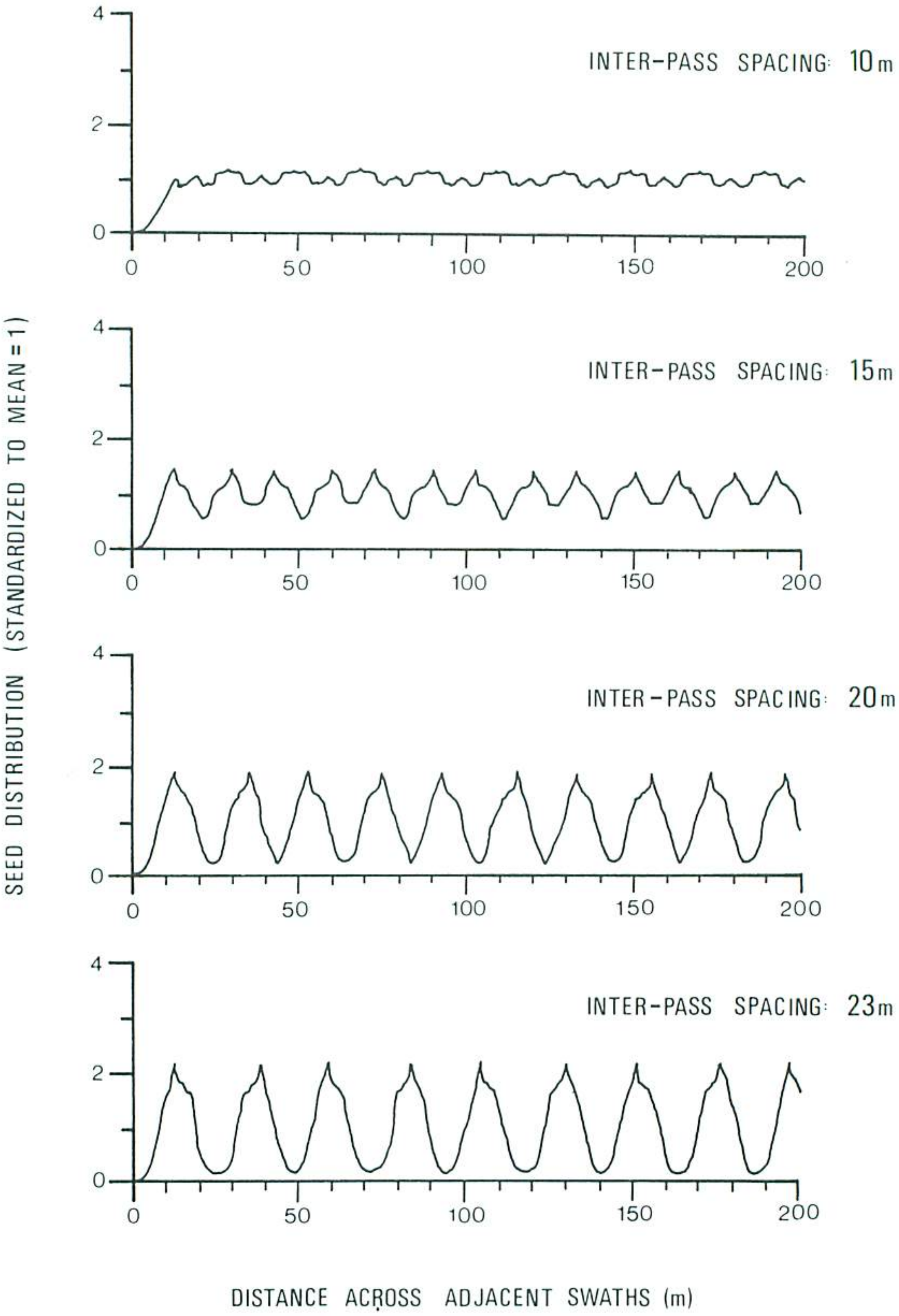

Figure 5. Expected seed distribution across adjacent swaths at four inter-pass spacings (assuming no variation in distribution along each flight path).

Seed distribution along the flight path also showed variation. Each auger revolution resulted in a 'pulse' of seed to the slinger and this produced a wave-like pattern of distribution. The number of waves per unit length along the flight path increased directly with auger speed (Fig. 6), but their relative amplitude decreased as the actual deposit increased (Fig. 7).

Expected multiple-pass distribution variances at various inter-pass spacings for application rates of 50,000, 100,000 and 150,000 seeds/ha were determined by combining the distribution patterns along the flight path and across the swath. At narrow spacings, the distribution pattern along the flight path results in a sizeable increase in variance at each rate (Fig. 8). However, as inter-pass spacing, and therefore output rate, is increased for a given application rate, the relative amplitude of this pattern and its influence on distribution variance declines. At spacings greater than 16 m at 150,000 seeds/ha and 24 m at 100,000 seeds/ha the distribution pattern along the flight path no longer contributes significantly to overall distribution variance. However, at 50,000 seeds/ha the output rate is never great enough at any of the spacings considered to overcome the influence of this pattern, and distribution variance remains extreme throughout.

The combined effects on expected seed distribution of the distribution patterns across the swath and along the flight path at four inter-pass spacings are illustrated in Figure 9.

The ability of the pilot to maintain the prescribed inter-pass spacing can also influence distribution characteristics. Simulation studies of this aspect indicate that randomly occurring course errors of up to 2 m from the prescribed flight path have little effect on overall distribution variance (Fig. 10). However, random errors of up to 5 m, or greater, increase expected distribution variance substantially, particularly at prescribed spacings of 10-20 m.

Factors Influencing Seed Distribution

The relationships between wind conditions, flying height, aircraft speed and distribution characteristics (Table 3) were investigated through correlation analysis (Table 4) and, where appropriate, linear regression. The results are presented separately for each of seven distribution characteristics.

Pattern offset: Pattern offset is the distance from the vertical projection of the center of the flight path to the point of peak seedfall in the swath. Two indices were used: relative pattern offset, in which distances to the right of the flight path were positive and those to the left were negative; and offset distance, a simple measure of distance regardless of direction. Relative pattern offset was strongly correlated (r = 0.95) with the relative crosswind vector (wind vector from left to right across the flight path). In calm conditions, distribution across the swath peaks slightly (1 m) to the left of center of the flight path (Fig. 11). However, even light crosswinds cause substantial shifts in deposit location, as each km/hr of crosswind displaces the pattern approximately 3.6 m. Offset distance was not significantly correlated with flying height, but the pilot tended

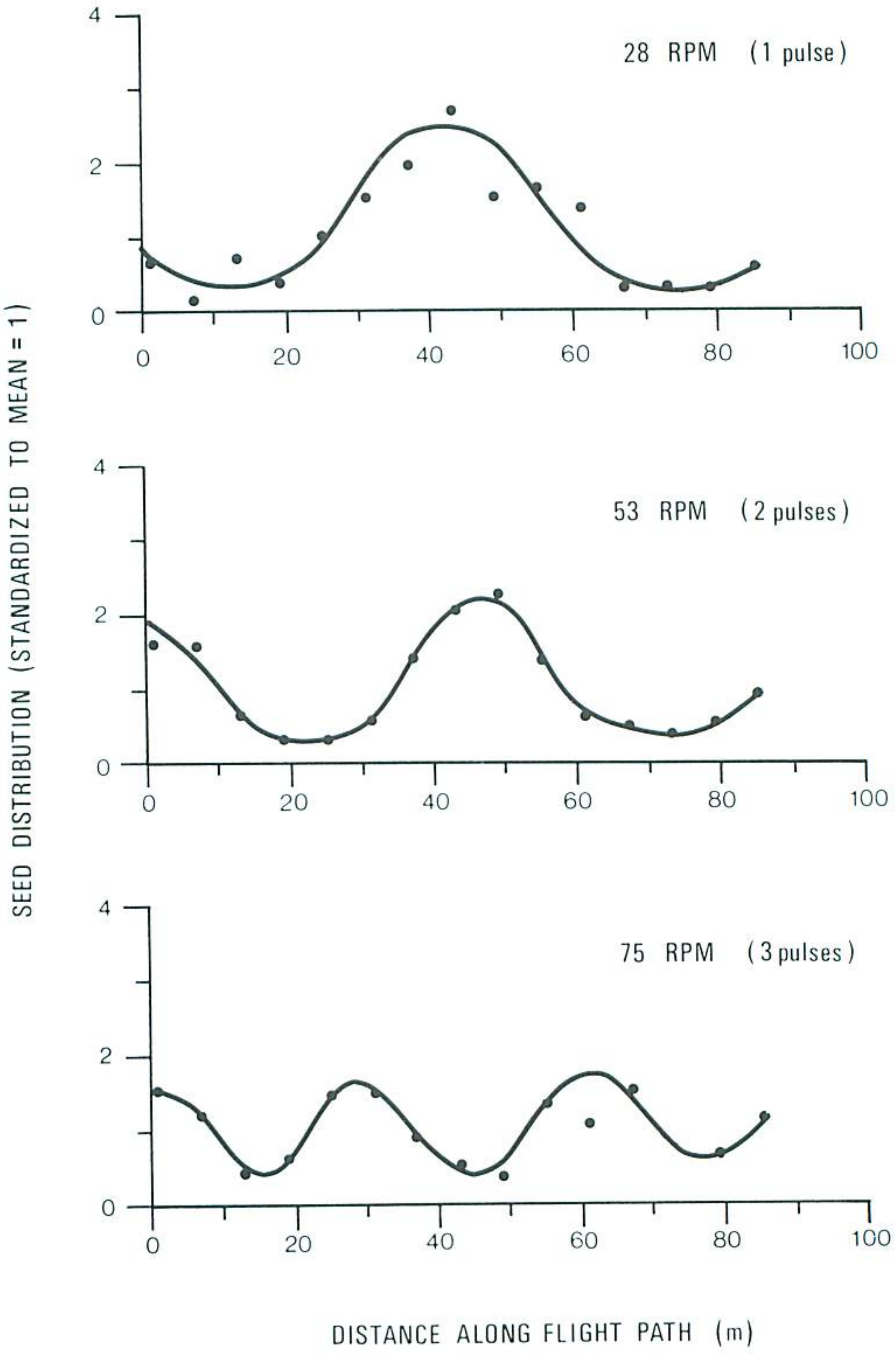

Figure 6. Seed distribution along the flight path for representative flights at three different auger speeds, corresponding to approximately one, two and three pulses of seed per 86 m.

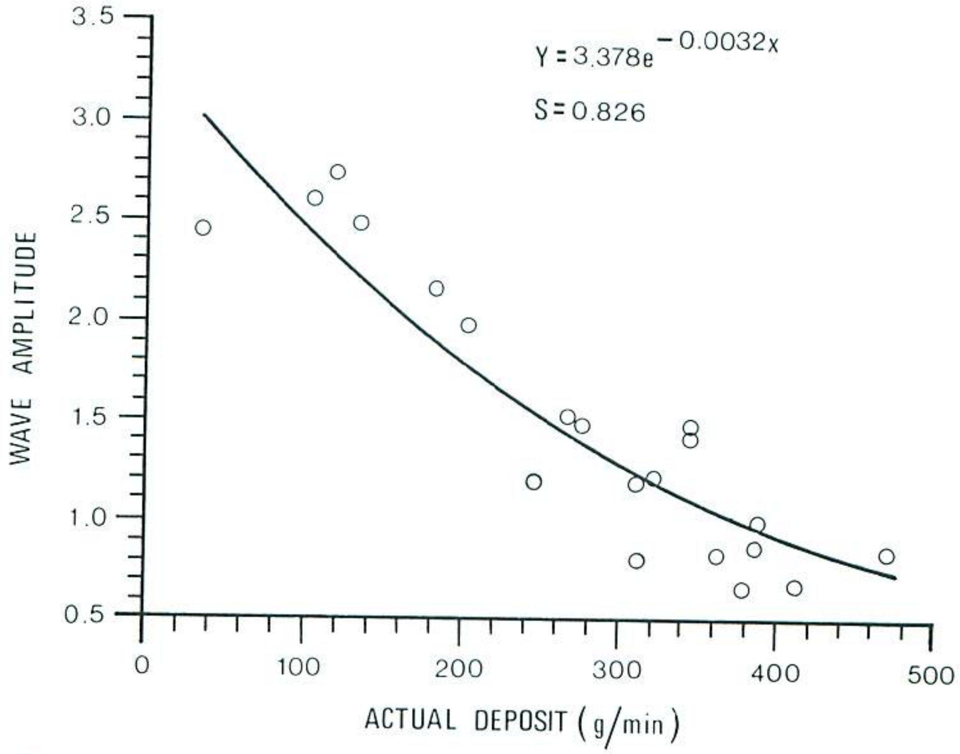

Figure 7. Influence of actual deposit on relative wave amplitude (maximum deposition per wave/minimum deposition per wave) of the distribution along the flight path.

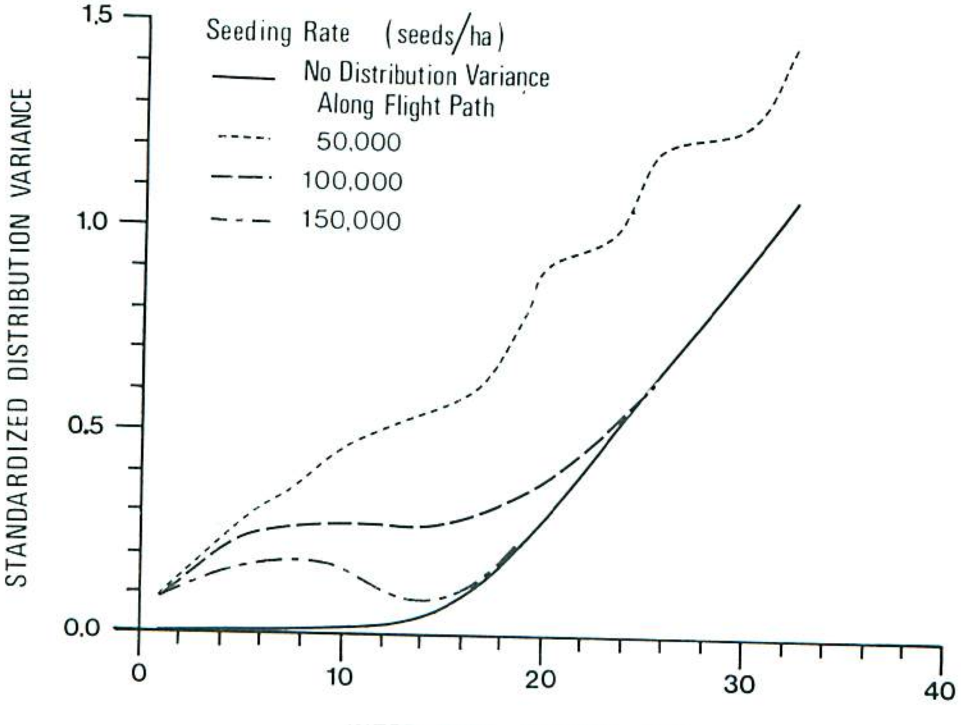

Figure 8. Expected multiple-pass distribution variance as a function of inter-pass spacing.

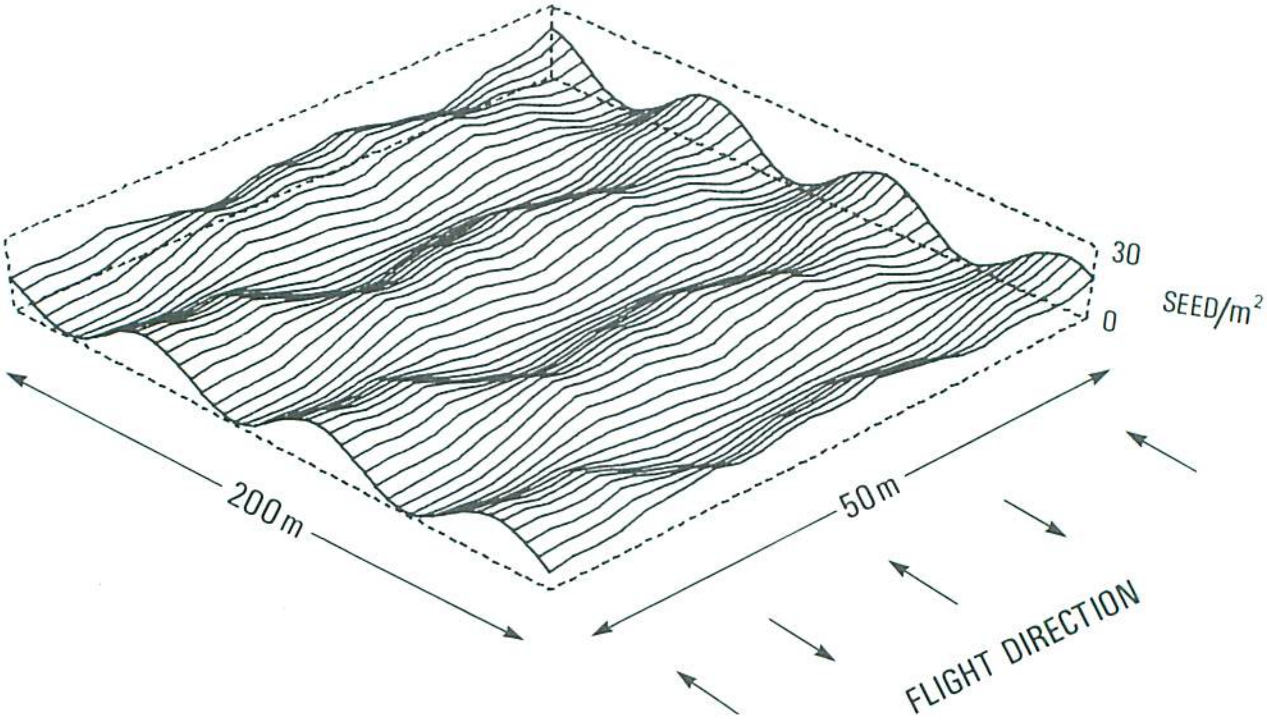

Figure 9a. Expected seed distribution at 10-m inter-pass spacing, 100,000 seeds/ha.

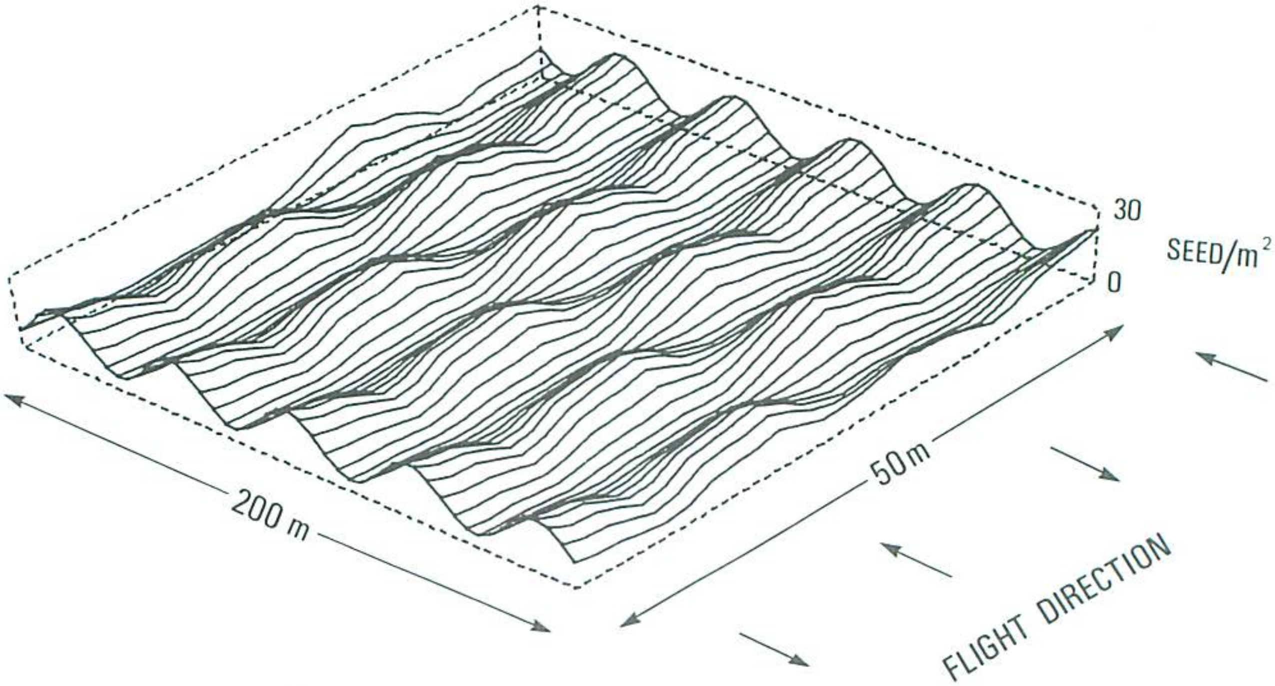

Figure 9b. Expected seed distribution at 15-m inter-pass spacing, 100,000 seeds/ha.

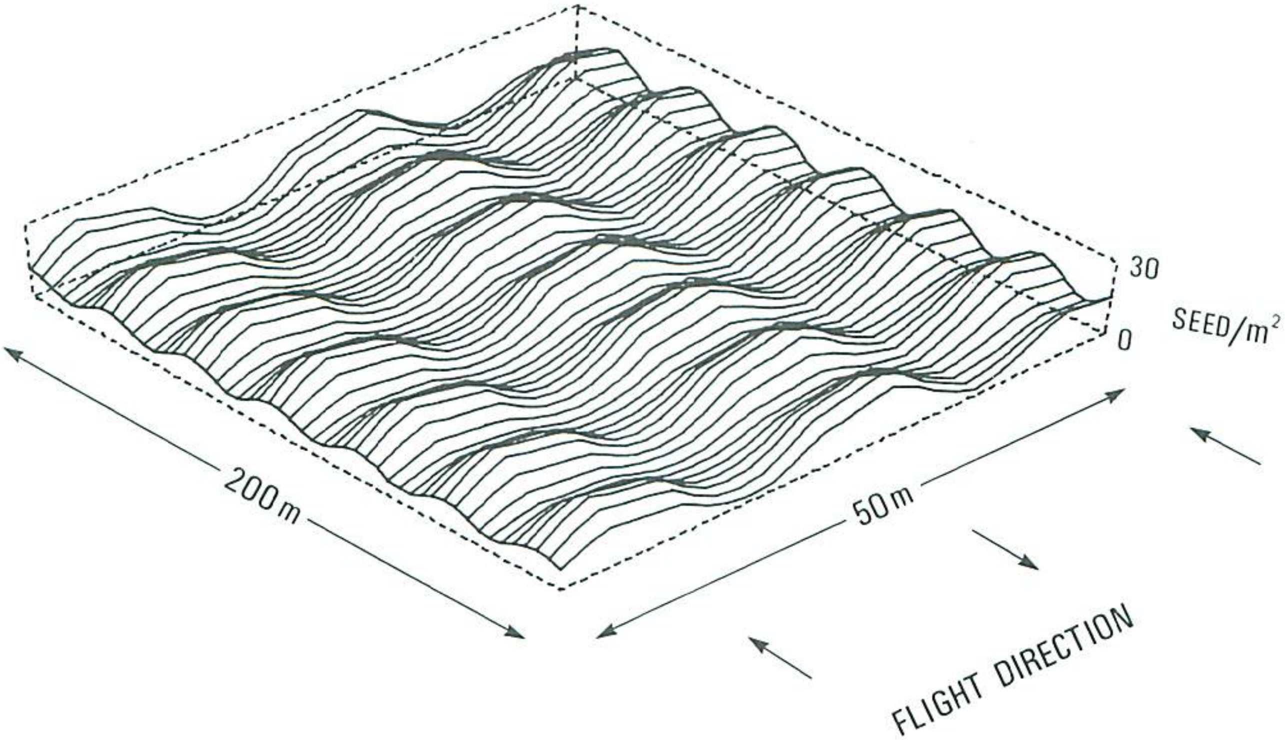

Figure 9c. Expected seed distribution at 20-m inter-pass spacing, 100,000 seeds/ha.

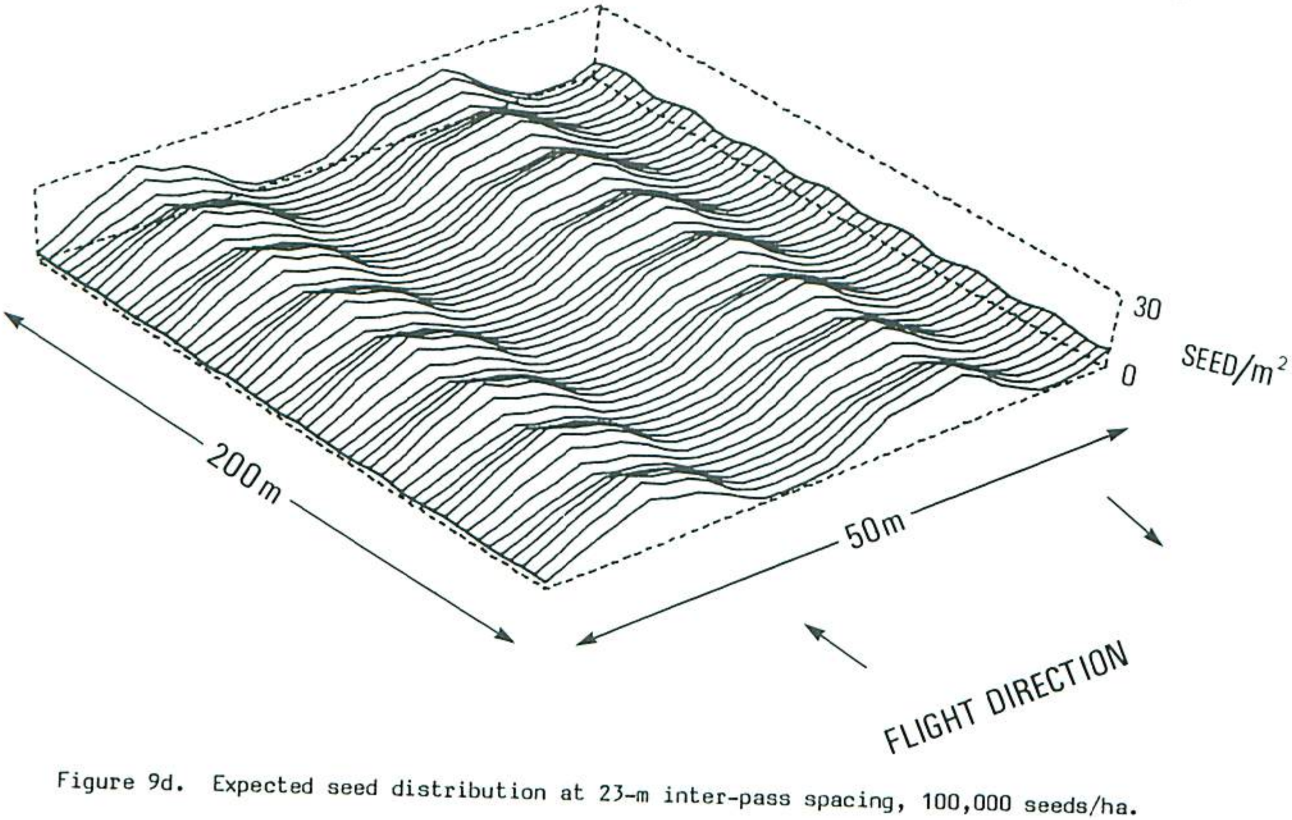

Figure 9d. Expected seed distribution at 23-m inter-pass spacing, 100,000 seeds/ha.

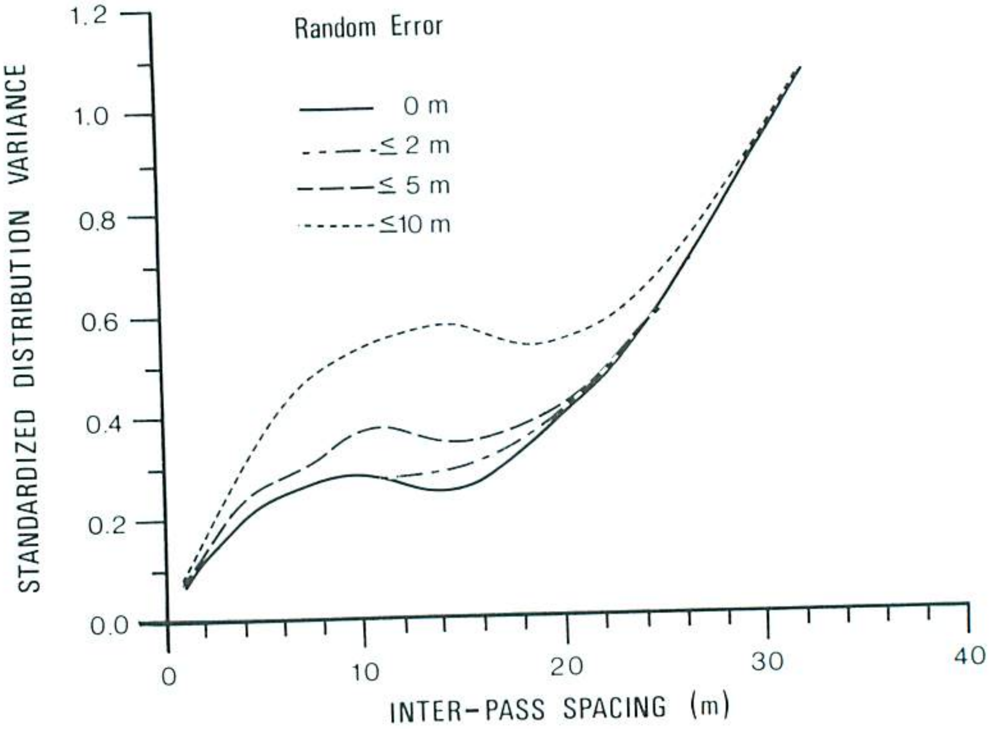

Figure 10. Effect of random deviations from the prescribed flight path on expected multiple-pass distribution variance at various inter-pass spacings, 150,000 seeds/ha.

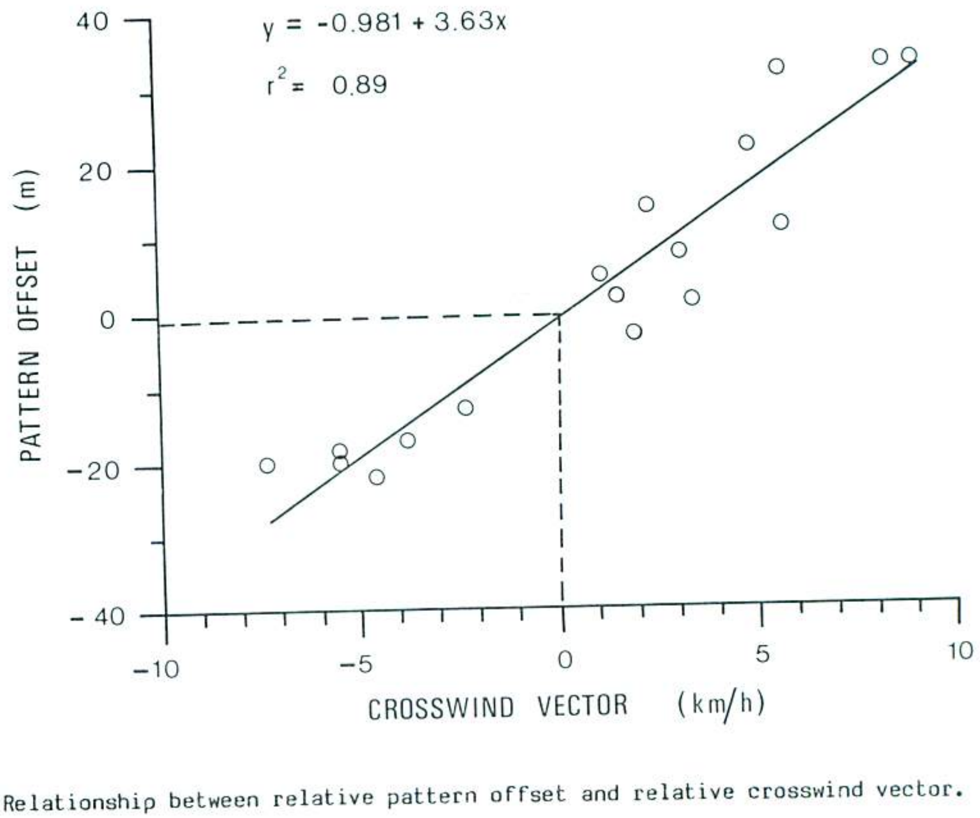

Figure 11. Relationship between relative pattern offset and relative crosswind vector.

Table 3. Seed distribution characteristics and related wind conditions, aircraft speeds and flying heights, all flights combined.

Characteristic	Mean	Standard deviation	Range
Relative crosswind vector (km/hr)	1.09	4.91	-7.4 - 9.0
Absolute crosswind vector (km/hr)	4.32	2.37	1.1 - 9.0
Headwind vector (km/hr)	-1.69	4.76	-9.2 - 8.3
Aircraft ground speed (km/hr)	133.7	9.58	113.5 - 148.5
Flying height (m)	23.6	5.79	14.5 - 34.5
Deposit rate (seeds/array)	522.4	245.1	68 - 917
Practical swath width (m)	14.5	1.96	12 - 18
Relative pattern offset (m)	2.26	18.41	-22 - 33
Offset distance (m)	14.7	10.80	0 - 33
Skewness of distribution across the swath	0.05	0.12	-2.2 - 0.25
Kurtosis of distribution across the swath	1.18	1.94	-0.63 - 6.05
Relative distribution amplitude along the flight path	1.51	0.67	0.66 - 2.74

to fly lower in these trials as the crosswind vector increased. There were no other significant correlations or interactions between pattern offset and wind characteristics, flying height or aircraft speed.

<u>Practical swath width</u>: Practical swath width is the average minimum width of swath on which at least 90% of the seed is deposited during a single pass. This measure disregards the sporadic seedfall that occurs at the tails of the swath. This seedfall has little impact on overall distribution, but it confounds attempts to relate swath width to other factors. Practical swath widths of the 21 flights ranged from 12 m to 18 m, whereas total swath widths were generally 25 m to 30 m. Crosswinds tended to increase the practical swath width somewhat ($r = 0.58$). Consequently, wider swaths were also associated with greater offset distances ($r = 0.69$).

Table 4. Correlation matrix of factors associated with seed distribution.

	Factor										
Factor	Relative crosswind vector	Absolute crosswind vector	Headwind vector	Aircraft speed	Flying height	Deposit rate	Practical swath width	Relative pattern offset	Offset distance	Skewness of distribution across the swath	Kurtosis of distribution across the swath
Absolute cross-wind vector	0.18										
Headwind vector	-0.04	-0.17									
Aircraft speed	-0.29	-0.19	0.86								
Flying height	0.04	-0.39	-0.09	-0.05							
Deposit rate	0.26	0.29	-0.28	-0.21	-0.43						
Practical swath width	0.20	0.58	-0.12	-0.20	-0.23	-0.19					
Relative pattern offset	0.95	0.30	-0.13	-0.39	0.02	0.19	0.42				
Offset distance	0.18	0.83	-0.43	-0.40	0.03	0.10	0.69	0.38			
Skewness of distribution across the swath	0.48	-0.16	0.07	-0.05	0.10	-0.36	0.15	0.50	0.05		
Kurtosis of distribution across the swath	-0.23	0.18	0.19	-0.01	0.14	-0.41	0.18	-0.05	0.28	0.10	
Relative distribution amplitude along flight path	-0.38	-0.11	0.20	0.16	0.33	-0.86	0.18	-0.31	-0.13	0.16	0.44

n = 18, P (0.05) = 0.47 (Three flights were omitted because of incomplete data for all factors.)

Skewness and kurtosis of seed distribution across the swath: Two measures were used to characterize the shape of the distribution pattern across the swath: skewness (coefficient of skewness [Snedecor and Cochrane 1980]), a measure of the symmetry of the distribution pattern about the mean; and kurtosis, a measure of the length of the tails of the distribution pattern in relation to its peak.

Skewness, which was determined for the practical swath width, was directly correlated with the relative crosswind vector (r = 0.48). Winds from the left compressed the left-hand tail of the distribution and extended the right-hand tail, whereas winds from the right had the opposite effect. Consequently, skewness and relative pattern offset were also directly related (r = 0.50). Under calm conditions, the swath pattern is slightly skewed to the right.

Kurtosis, which was measured over the entire swath width, was not significantly related to wind conditions, flying height, aircraft speed or deposit rate.

Distribution amplitude along the flight path: The relative amplitude of the wave-like distribution pattern along the flight path was inversely related (r = -0.86) to deposit rate, but was not significantly correlated with flying height, aircraft speed or wind conditions.

DISCUSSION

Deposition

Although mean normalized deposition at each output rate was below that prescribed, in no case did it differ significantly from ±10% of the application rate. At the two higher rates, mean shortfalls (6-12%) were considerably less than those found with jack pine and variation in deposit from flight to flight was comparable (cf. Foreman and Riley 1979). At the lowest rate, the mean catch was only 60% of that prescribed and deposit from flight to flight was highly variable, but this was likely a result of the sampling procedures used and the small sample size.

At the lowest prescribed output rate (148 g/min at an aircraft speed of 138 km/hr) the 86-m-long seed trap array received less than one full auger revolution of seed, and consequently failed to catch part of the peak or the trough of the distribution pattern along the flight path during each pass. In fact, the seed trap layout used likely resulted in overestimates of variation in deposit at all rates, the size of the error decreasing as the number of auger revolutions, or 'waves', falling within the array increased.

Another factor contributing to the large disparities in deposit at the lowest rate was insufficient lead time in activating the seeder. The auger requires one or two revolutions to reach the proper rotation speed. At lower output rates, the aircraft travels a greater distance during this startup period because each revolution of the auger takes longer. During these trials, the seeder was activated approximately 100 m before the aircraft reached the seed trap array. This is probably equivalent to less than one auger revolution (depending on the severity of the initial lag) at the lowest rate in comparison with two to three revolutions at the two higher rates. Hence, the unexpectedly low deposits at the 148 g/min output rate likely arose because deposit was measured before the auger attained the proper speed.

Deposit rates are also affected by such factors as the accuracy of seeder calibration, the variation in number of seeds per gram, differences between prescribed and actual aircraft ground speeds, and the variability associated with output rates. It is evident from Table 1 that, over a 30-second period, the auger dispenses a consistent output regardless of setting, and is unlikely to cause major fluctuations in deposit. Average aircraft ground speed per flight varied somewhat during these trials, but adjusting deposit to account for this did not reduce the variation substantially. However, another source of calibration error, in addition to those outlined by Foreman and Riley (1979), was found.

During calibration the auger produces a significant drain on the aircraft battery, and this results in progressively lower auger speeds at a given setting when the battery is not being recharged. To compensate for this, the power supply should be supplemented during calibration. However, despite this concern, there was no evidence to suggest that this seeder/aircraft combination cannot meet a mean deposit standard of ±10% of the application rate (Foreman and Riley 1979) when sowing black spruce seed.

Distribution

The slight skewness associated with black spruce seed distribution across the swath is a function of propeller rotation. Distribution patterns with single-engine, fixed-wing aircraft are shifted in the direction of propeller rotation, i.e., to the left with clockwise propeller rotation[9] (Armstrong 1978). Black spruce seed distribution across the swath is more symmetrical than that of jack pine with this seeder/aircraft combination, but the practical swath width is narrower (15 m vs ≈ 20 m) (cf. Foreman and Riley 1979). As a result, expected distribution variances across the swath are lower than those of jack pine at narrow inter-pass spacings (Fig. 4), but at wider spacings the situation is reversed.

Unfortunately, a wave-like distribution pattern along the flight path can also occur with black spruce, and this magnifies expected distribution variance: the greater the relative wave amplitude the larger the expected variance. Because relative wave amplitude varies inversely with deposit and therefore auger speed, this problem can be addressed by decreasing seed output per

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[9] Most light propeller-driven aircraft in North America have clockwise propeller rotation (as viewed from the cockpit).

revolution, so that a greater auger speed is required to obtain a given output rate. For instance, this could be accomplished by narrowing the pitch of the auger (if this does not cause greater mechanical abrasion and thereby reduced seed viability) or by combining the seed with a 'filler' such as non-viable agricultural seed, of the same size, shape and density.

To determine which seeding rate/inter-pass spacing combinations are likely to result in adequate seed distribution, a distribution standard is needed. Foreman and Riley (1979) recommended that minimum deposition on a 4-m^2 basis over all of the area sown be ⩾50% of the mean deposit rate. However, even when seed is distributed at random, seed catch from trap to trap varies considerably. Consequently, at least some 4-m^2 quadrats are likely to receive less than 50% of the mean deposit rate through chance and through slight variations in sowing conditions from pass to pass, regardless of expected distribution uniformity. Ballard and Will (1971) used the term 'half value' to indicate the proportion (%) of the target area receiving less than 50% of the designated rate during aerial applications of fertilizer, and proposed that a half value of 10(%) or less be considered acceptable. To conform with this fertilization standard and address the variability associated with seed distribution, we recommend that Foreman and Riley's (1979) standard be revised to read: minimum seed deposition on a 4-m^2 quadrat basis should be ⩾50% of the mean deposit rate over ⩾90% of the seeding chance.

When this revised standard is applied to the black spruce data (Fig. 12) it is evident that, with the current auger, seeding rates of 50,000 and 100,000 seeds/ha do not result in adequate distribution at practical inter-pass spacings. At a seeding rate of 150,000 seeds/ha, acceptable distribution can be obtained at inter-pass spacings of 11-16 m because the auger revolves fast enough to minimize variations in distribution along the flight path. If seed could be distributed uniformly along the flight path[10], inter-pass spacings of up to 16 m could result in satisfactory seed distribution, regardless of seeding rate[11].

In the analysis so far, the assumption has been made that inter-pass spacing is maintained perfectly. However, random deviations of the aircraft from the prescribed flight path are inevitable and can increase expected distribution variance (Fig. 10) and half values (Fig. 13) substantially. Randomly occurring deviations of up to 2 m have little effect at a sowing rate of 150,000 seeds/ha, but those of up to 5 m result in expected half values greater than 10 regardless of inter-pass spacing. This underscores the need to select conscientious, capable pilots and to provide adequate flagging of flight lines.

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[10] Following these trials, General Airspray Ltd. increased the pitch of its black spruce augers to reduce distribution variance along the flight path (D. Worgan, General Air spray Ltd., personal communication).

[11] Once the variation in distribution along the flight path has been overcome, expected distribution variances and half values will be identical for all seeding rates because the shape of the distribution pattern across the swath, the major remaining source of variation, is not rate-dependent.

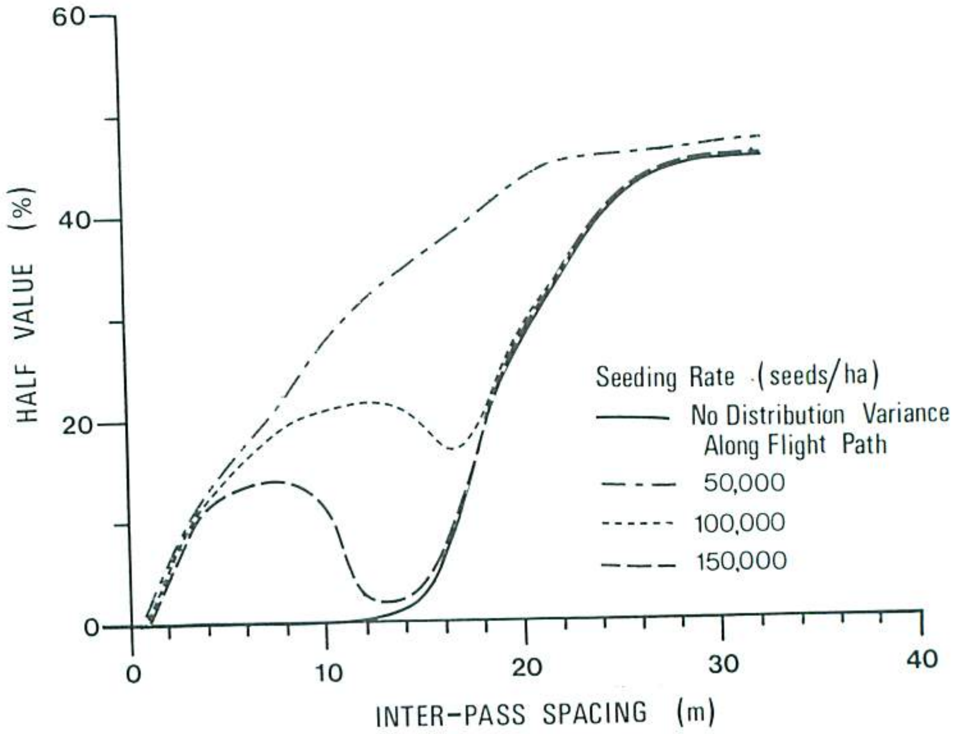

Figure 12. Influence of inter-pass spacing on expected half values (the proportion of the seeding chance expected to receive less than half of the mean deposit rate).

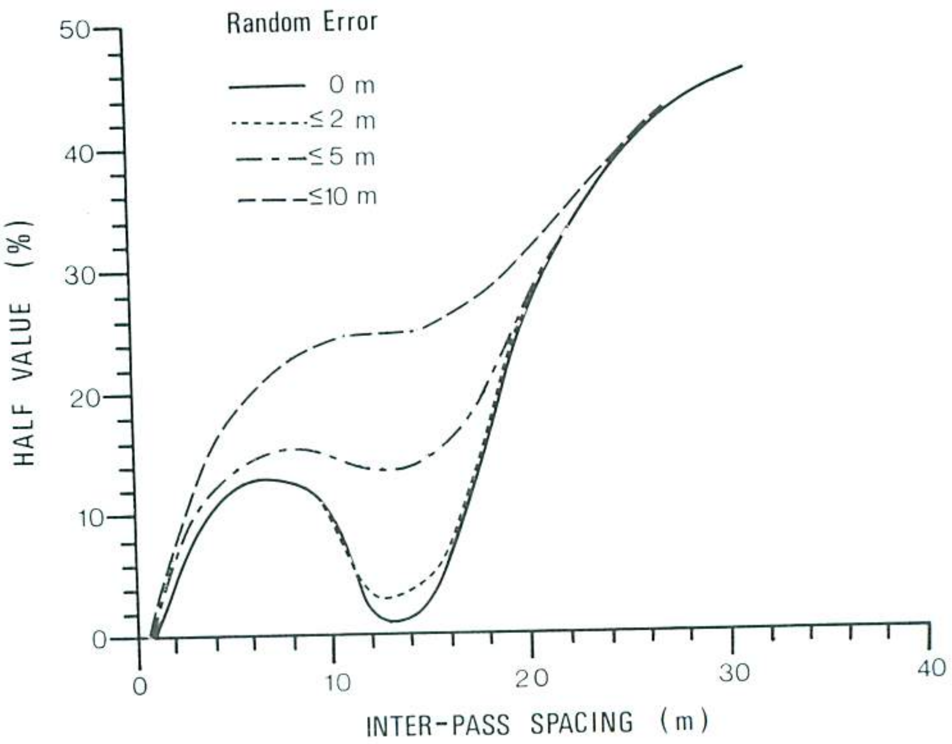

Figure 13. Effect of random deviations of the aircraft from the prescribed flight path on expected half values at various inter-pass spacings, 150,000 seeds/ha.

In the selection of an appropriate inter-pass spacing, the results of these simulations should be considered in conjunction with practical constraints. For example, the preceding analyses presuppose that wind speed, wind direction, and flying height are constant throughout a seeding job, conditions that rarely occur. As a result, actual distribution variability will likely exceed the expected values presented herein. Yet for seeding to be most cost effective, inter-pass spacing should be as wide as distribution characteristics permit.

It is recommended, therefore, that an inter-pass spacing of 15 m be used when black spruce is being sown with this seeder/aircraft combination. This should minimize variations in seed distribution and should not increase seeding costs dramatically.

These results also provide new insight into the poor stocking that has generally resulted from aerial seeding of black spruce in the past. Since 1968 most seeding in Ontario has been carried out with this seeder/aircraft combination (Brown 1973), at inter-pass spacings of 20-23 m (Worgan 1973). At these inter-pass spacings, even under the best conditions, at least 25-40% of any given black spruce seeding chance likely received less than half the mean deposit rate. While other factors such as too little receptive seedbed and/or adverse weather may have been primarily responsible for the poor results, inadequate seed distribution undoubtedly contributed (cf. Armson 1972).

Wind Conditions, Flying Height and Aircraft Speed

Wind conditions, flying height and aircraft speed have a significant impact on seed deposition and distribution, but with adequate precautions, negative influences can be minimized. Over all, steady winds of less than 10 km/hr (measured 1.5 m above ground) have only a minor effect on distribution efficiency. Crosswinds increase the practical swath width and the skewness of the distribution pattern somewhat, and the pattern is readily offset from beneath the aircraft track, but with steady crosswind vectors of less than 10 km/hr, its basic shape is maintained. At crosswind vectors greater than this, the distribution pattern may break down and seed may be scattered widely.

Pattern offset is not a problem if wind speed is constant because succeeding passes are likewise offset, regardless of flight direction (Fig. 11). However, variable or shifting winds can increase distribution variance and half-values dramatically because successive swaths are offset to varying degrees. Although it was not evident in these trials, flying height can also influence pattern offset. In general, the higher the aircraft (i.e., the greater the vertical distance over which wind can influence deposit location) the more the pattern will be offset by a given crosswind vector. To minimize variation and reduce overlapping and gaps in the distribution pattern, all passes should be flown at similar heights. As well, to avoid excessive drift and ensure that the entire target area is seeded, flying heights should be as low as operational conditions permit (i.e., 25-30 m on clearcut sites). Distribution patterns on areas with large variations in topography or with residual trees that impair seed distribution and force the pilot to alter the flying height will undoubtedly be poorer.

Aircraft ground speed, within the range examined, did not affect seed distribution characteristics. However, once the speed has been selected and used in the calibration calculations, it should be strictly adhered to because of its direct bearing on seed deposition. Differences between actual and prescribed aircraft ground speeds produce commensurate disparities between deposit and application rates.

Output rate has a direct bearing on seed distribution along the flight path, with more uniform distribution being achieved at higher output rates. In view of the importance of seed distribution to the achievement of optimum stocking, consideration should be given to sowing at higher rates whenever possible.

RECOMMENDATIONS FOR OPERATIONAL SEEDING

On the basis of these trials, the following recommendations are made for operational seeding of black spruce with the Brohm Seeder/Piper PA-18A aircraft combination:

1) Calibrate the seeder carefully using a precise balance, and accurately determine the number of seeds per gram at the time of calibration. The seeding unit should be warmed up prior to calibration, particularly if the ambient temperature is low (<10°C), and the electrical power supply to the unit should be supplemented if the aircraft battery is not being recharged during calibration.

2) Sow at 15-m inter-pass spacing, and provide ground guidance to help the pilot maintain proper spacing.

3) To avoid large variations in distribution along the flight path, do not sow at auger speeds of less than 70-75 rpm[12].

4) Seed only when wind speeds 1.5 m above ground are less than 10 km/hr, and avoid seeding when winds are variable or shifting, regardless of average wind speed.

5) Select a reasonable flying height (25-35 m) and aircraft ground speed (130-150 km/hr), and maintain these throughout the seeding operation. This is of much greater benefit than attempting to fly as low or as slowly as possible.

Above all, calibration and flying procedures must be carried out carefully and consistently if satisfactory seed deposition and distribution are to be realized.

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[12] This corresponds to an output rate of approximately 395 g/min and a seeding rate of approximately 125,000 seed/ha at 15-m inter-pass spacing and an aircraft ground speed of 140 km/hr, with the present auger.

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APPENDIX

CALIBRATION OF THE BROHM SEEDER

The seeder is calibrated on the ground over 30-second intervals to meter seed at the prescribed output rate for the proposed aircraft ground speed, inter-pass spacing and application rate. The speed of the auger is adjusted until the calculated weight of seed equivalent to the prescribed output rate is obtained consistently over 30-second intervals.

Calculations

Area (ha) covered per minute of flight

$$= \text{Aircraft ground speed (m/min)}. \ \frac{\text{inter-pass spacing (m)}}{10{,}000}$$

Weight (g) of seed required per ha

$$= \frac{\text{Application rate (seed/ha)}}{\text{No. seed/g}}$$

Output rate (g of seed) required per 30-second interval

$$= \frac{\text{(area covered per min of flight).(g of seed required per ha)}}{2}$$

(from Foreman and Riley 1979).