FACTORS AFFECTING AERIAL DISTRIBUTION OF FERTILIZERS TO FORESTS

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ABSTRACT

This paper examines several major causes of irregular fertilizer dispersal from helicopters and airplanes. Factors of particular importance include the pilot's experience, his ability to maintain accurate flight patterns, and physical properties of the products being applied. Spreading equipment must be properly designed to deliver correct quantities of material in swaths of adequate width, and treatment units should be suitably arranged and demarcated. Adverse weather conditions, especially strong and gusting winds, can also produce an unsatisfactory distribution of fertilizer.

INTRODUCTION

The extent of fertilizer applications to forests, using helicopters and fixed-wing aircraft, has increased substantially throughout the Pacific Northwest during the past 15 yr. In Washington and Oregon, the Weyerhaeuser Company commenced operational fertilizing in 1967, with a program involving 500 ha (Belluschi 1972), and, less than a decade later, a project of 95 000 ha was accomplished in a single year. Crown Zellerbach's fertilizer operations began in 1965 with an area of only 600 ha (Strand et al. 1973), but have since expanded to cover about 12 000 ha annually.

Until recently, the extent of forest fertilizing in British Columbia was minimal compared with activities in Washington and Oregon, but Pacific Logging Co., Ltd., has been applying urea since 1963 (Crown 1974), and by 1977 the total area fertilized by all companies was approximately 15 000 ha. In 1978 the British Columbia Ministry of Forests conducted its first significant operational fertilizing, involving a modest 3000 ha, but the program for 1979 comprises 20 000 ha and a budget of $2.5 million.

The ability to spread the correct quantity of fertilizer within the designated treatment unit, and so achieve the required *average* rate of aerial application, is frequently interpreted to indicate a uniform pattern of distribution has been obtained throughout. This optimism is not shared by the author following involvement in several operational projects;[1],[2] studies conducted by others confirm that aerial applications using helicopters[3],[4] (Strand 1972, Edwards 1977, Olson 1979a) and fixed-wing aircraft[5] (Armson 1972, Mahendrappa 1976) often result in extremely irregular dispersal.

Because inconsistent patterns of fertilizer distribution can adversely affect silvicultural and economic benefits obtained from the treatment, it is necessary to identify and measure those factors that prevent satisfactory applications. This paper examines several major causes of irregular fertilizer dispersal, and suggestions are made for improved techniques. The need is explained for continued studies to assess the performance of the pilot and his equipment, and benefits are demonstrated that result from close liaison among fertilizer manufacturers, aviation engineers, applicators, and foresters.

FACTORS AFFECTING FERTILIZER DISTRIBUTION

FEATURES OF TREATMENT UNITS

Shape, Size, and Demarcation

Because fertilizer is most conveniently applied in straight swaths, square or rectangular treatment units are easier to fly

1. P. R. Barker, 1975. Fertilizer monitoring results. *In* Aerial fertilization, T.F.L. No. 2, 1975, Project 2-007, 10 p. Crown Zellerbach Can. Ltd. Unpubl. Rep.

2. P. R. Barker, 1979. Monitoring of rate and uniformity of application in Vancouver Region's 1978 fertilization operations. 8 p. Res. Branch B.C. Minist. For. Unpubl. Rep.

3. H. W. Anderson, 1969. Procedures and evaluation of tests conducted on fertilizer dissemination equipment—Rosenbalm Aviation and Western Helicopter Services. 24 p. State Wash. Dep. Nat. Resour. For. Land Manage. Cent. Unpubl. Rep.

4. L. E. Witsell, 1971. Evaluation of the application of urea materials by helicopter. Shell Dev. Co. Modesto, Calif. Unpubl. Rep. 77 p., illus.

5. E. H. Mallonee and R. F. Strand, 1975. Work plan and establishment report for 1974 aerial fertilization at Tsolum Flat—T.F.L. 2. 27 p. Crown Zellerbach Can. Ltd. Unpubl. Rep.

compared with areas of irregular shape; fertilizer distribution can be unsatisfactory if the pilot has to follow sinuous boundaries or undertake complex maneuvers to cover asymmetric blocks. Boundaries of each unit must be clearly visible from the air to ensure all of the required area is treated without applying fertilizer outside the block. Boundary errors, involving parts of the unit remaining unfertilized together with portions of surrounding stands inadvertently being treated, can correspond to 7%–14% of the size of blocks smaller than 25 ha, while for larger units the error may only be 1%–2% (Strand 1972).

Wherever possible, distinctive natural outlines such as creeks, ridgetops, canyons, and contrasting forest-cover types should be used as boundaries, in addition to manmade features including roads and power lines. If necessary, boundaries must be specially marked using flags, helium-filled balloons, or other devices. The numbers of such markers should be minimized to ensure adequate delineation of the unit without causing confusion for the applicator (Evans 1972), and their positions should be accurately shown on aerial photographs for the pilot's reference.

It is most convenient if one full load of fertilizer can be spread in an exact number of complete passes across the treatment unit, and dimensions of the block should, if possible, be determined accordingly. If the material is expended before a pass is finished, the pilot might experience difficulty in relocating his position to commence spreading the next load (Clark 1968, Mahendrappa 1976); this can result in parts of the area being untreated, some portions receiving dual application, or both.

When measuring the size of a treatment unit to calculate the required quantity of fertilizer, it is necessary to use maps rather than aerial photographs, since the latter are subject to scale errors caused by distortion. Accurate knowledge of the fertilizer requirement for each individual block ensures the correct average rate is applied.

Topography

Flying over steep or irregularly contoured land is less conducive to uniform fertilizer distribution, compared with operations involving flat terrain. In mountainous topography, the entire treatment unit might not always be discernible to the pilot, and sufficient ground markers must be used to ensure boundaries are conspicuous from several aerial positions. On hillsides and at higher elevations, air turbulence and poor visibility can occur more frequently than on level terrain at lower altitudes, especially in autumn and winter.

In addition, it is often difficult for the applicator to maintain a constant airspeed, and an accurate height above the tree canopy when operating over irregular topography. This combination of factors suggests the pattern of fertilizer distribution is probably less consistent in mountainous regions than on lowland sites, and standards specified for the applicator's performance might require appropriate adjustment if adverse topographic features predominate.

DESIGN OF EQUIPMENT

Simplex-Type Systems[6]

A frequent method of fertilizer application uses a Simplex-type bucket suspended approximately 6 m beneath a helicopter. Buckets that are aerodynamically unstable can swing or gyrate, which limits the pilot's ability to spread in straight swaths and contributes to irregular distribution of material. Stability can be improved by attaching a fin to the bucket, provided the correct position and optimum fin size are determined.

The Simplex-type bucket uses a revolving impeller to disperse the fertilizer; this equipment consists of a metal disc, approximately 60 cm in diameter, through which several vanes extend from the center to the circumference. When the aperture of the bucket is opened, fertilizer is gravity-fed to the center of the rotating impeller, and is thrown out through the vanes.

Our applicator in British Columbia has so far used impellers in which the depth of the vanes tapers from 50 mm at the circumference to only 6 mm at the center, but a new design is currently being tested in which the vane depth is 50 mm throughout. It is believed this modification will improve the flow of fertilizer, reduce the possibility of clogging caused by lumps and foreign material, and perhaps enhance the uniformity of application.[7]

Another suggestion for altering impeller design is to adopt a "swept-back" configuration for the vanes, which might reduce the impact of fertilizer passing through, and therefore decrease breakage of the granules.[7] Particle breakage is insignificant at impeller speeds of 650 r/min,[4] but could be more important at greater speeds (Brown 1972).

The Simplex-type system usually produces a fertilizer swath 30–45 m wide (Anderson 1970), although narrow swaths of only 20 m have been used[4] (Olson 1979b), and widths of 60 m are feasible (Belluschi 1972). Theoretically, greater swath widths can be obtained by increasing the angular velocity of the impeller, which is related to the radius and revolution speed of the disc.[8] In a field test, a change in spinner speed from 650 r/min to 800 r/min often increased swath width, and improved uniformity of fertilizer distribution within the swath.[4] Presumably, spreading in wider swaths contributes to

6. The use of trade, firm, or corporation does not constitute official endorsement by the B.C. Ministry of Forests of any product or service to the exclusion of others which may be suitable.

7. N. Perkins, Conair Aviat. Ltd., Abbotsford, B.C.

8. D. C. Young, 1970. Mathematical analysis of variables affecting drift and swath width of helicopter applied prilled urea for forest fertilization. 11 p. Tech. Memo. Res. Dep. Union Oil Co. Calif., Union Res. Cent., Brea, Calif.

more precise application throughout the treatment unit, since fewer flight lines are involved and accuracy of overlapping is greater.

The impeller is driven by belts connected to a small motor, and conventional belts tend to slip causing variations in spinner speed and consequent changes in swath width. The applicator conducting most operational fertilizing in British Columbia has recently adapted the impeller to use one notched gear-belt, which provides a positive drive and successfully eliminates slippage.

As the bucket empties under gravity, the head-pressure of fertilizer decreases, possibly causing a reduced flow of material and a smaller application rate farther along the swath. For a single test involving a swath 300 m long, application rate at the finish was 12% less than at the beginning,[3] but this variation is probably of minor significance compared with other sources of error.

Venturi-Type Systems

Fixed-wing aircraft generally use a venturi-type apparatus for spreading fertilizer. This equipment uses an air current produced by slipstream to direct the fertilizer past deflecting surfaces, resulting in a fan-shaped discharge. Initially, the venturi spreaders used for forest fertilizing were of a ducted design intended for agricultural projects, in which application rates normally approximate 100 kg/ha.

For forestry purposes, however, rates exceeding 400 kg/ha of fertilizer are common, and with these quantities the slipstream is less effective, intermittent clogging occurs in the ducts, and a very unsatisfactory distribution of material is obtained (Brazelton et al. 1968, Evans 1972). To overcome this problem, a V-shaped tetrahedron spreader has been developed (Evans 1972), which has only two deflecting surfaces and can accommodate larger rates of application; such equipment has been used extensively for fertilizing forests in British Columbia (Crown 1974).

Venturi-type spreaders usually produce a fertilizer swath width of 9 m (Clark 1968, Mannion 1977) to 18 m (Evans 1972, Crown 1974), although swath widths of 25–30 m are practicable (Mahendrappa 1976, Trayford and Taylor 1976). These swaths are narrow compared with the discharge normally obtained using disk impellers, indicating fertilizer distribution from fixed-wing aircraft is probably less precise than applications made with Simplex-type equipment attached to helicopters. Furthermore, venturi spreaders often produce individual swaths in which the lateral dispersal of material is very irregular (White 1956, Akesson and Yates 1962), and despite using overlapping flight patterns an extremely variable distribution of fertilizer can result[1,5] (Mahendrappa 1976).

Because of basic inefficiency of design (Amsden 1977), the possibilities are limited for improving venturi-type spreaders to obtain wider swaths and more uniform distribution of fertilizer. Aerodynamic drag and flight handling are adversely affected if the spreader is lengthened to achieve greater particle acceleration, or if discharge width is increased to assist fertilizer dispersal (Akesson and Yates 1962, Amsden 1977).

Innovative suggestions for significantly different designs include use of the slipstream to convey material through internal ducts toward the wing tips, with release points at various intervals producing a swath 25 m wide (Lee 1976). Theoretical calculations, however, indicate this system requires a uniform particle diameter of approximately 1 mm, and application rates of 40 kg/ha are feasible.

A more viable solution involves the installation of a rotary paddle distributor on either side of a central gage, positioned directly beneath the aircraft hopper (Yates et al. 1970). The rotors eject a portion of the fertilizer at 90° to the left and right of the flight line, while the remaining material is released directly into the airstream; for application rates of 340 kg/ha, this system produces a uniform distribution over a swath width of 18 m.

If fixed-wing aircraft continue to be used for applying fertilizer to forests, the need is suggested for further design studies to improve capabilities of existing equipment, to develop entirely new spreading techniques, or both.

PHYSICAL CHARACTERISTICS OF FERTILIZER

Particle Size

For a particular ejection velocity, large granules of fertilizer can achieve a greater lateral spread compared with smaller grains of similar specific gravity[8] (Yates et al. 1970), indicating particle size significantly affects swath widths obtained in aerial applications. Urea fertilizer, which is the type most commonly applied to forests in the Pacific Northwest, is available as "forestry grade" having particle diameters 3.4–6.7 mm, or "agricultural grade" with smaller granules of 1.2–2.4 mm diameter. When urea was applied using a helicopter equipped with a Simplex-type system, the swath width obtained from the larger granules was 45% (Switzer 1972) to 72% (Olson 1979b) greater compared with the spread produced by the smaller particles.

For urea applied by helicopter at 180 kg/ha, use of the forestry grade material gave a swath 36%–70% wider than that achieved with the agricultural grade, and at a rate of 90 kg/ha the larger granule spread twice the distance compared with the smaller particle.[4] Although Evans (1972) found the two different grades of urea produced similar swath widths using his venturi-type spreader, Lee (1976) considered particle size extremely significant in determining lateral dispersal from ram-air equipment, and Amsden (1977) estimated a granule diameter of 5–8 mm was optimum for venturi systems. In a comparison of two different size classes of ammonium nitrate fertilizer being spread from a fixed-wing aircraft, the product containing larger granules gave a 25% wider swath (Switzer 1972).

Besides providing a greater lateral spread, use of larger fertilizer particles also improves uniformity of distribution within an individual swath (Switzer 1972). Strand (1979) found variability in application rate was significantly less using forestry grade urea compared with the smaller-grained agricultural product, and Mannion (1977) obtained a more consistent distribution using a granulated superphosphate than with two fine-textured rock phosphates. Effects of wind partially explain the more regular dispersal of larger particles, since fine powders drift considerably (White 1956, Mannion 1977).

Interpretation of Young's[8] theoretical calculations indicate particles of the size occurring in agricultural grade urea tend to drift more readily than forestry grade granules, especially when dropped from 6 m or more above the canopy in winds exceeding 10 km/hr. Turbulence frequently occurs in mountainous forested terrain (Evans 1927), and in such conditions the superior dispersal of larger urea particles has been visually observed (Belluschi 1972) and quantitatively measured (Switzer 1972).

Another reason for the unsatisfactory aerial distribution of fine particles is their tendency for cohesion, which impedes mass flow (Amsden 1977), causing intermittent clogging of the discharge aperture (Conway 1962, Mannion 1977). Furthermore, if fertilizer contains a wide range of particle sizes, aircraft vibrations can cause stratification in the hopper (White 1956, Amsden 1977, Mannion 1977), resulting in a variable flow of material to the spreading apparatus (Ballard and Will 1971, Mannion 1977).

Although some reports suggest the tree canopy does not significantly obstruct aerial applications of fertilizers (White 1956, Ballard and Will 1971, Armson 1972), visual observations indicate considerable interception often occurs, especially with wet crowns (Olson 1972) and particles of small diameters (Belluschi 1972). Quantitative studies of interception involve several practical difficulties, but Barker[2] found 13%–47% of applied fertilizer was not recovered in traps placed under the canopy, and attributed this partly to obstruction by tree crowns. Olson (1979b) showed two different stands each intercepted approximately 30% of the forestry grade urea applied from a helicopter, but in similar locations about 70% interception occurred when the smaller-grained agricultural product was used.

In a study that simulated aerial application of several fertilizers to individual trees, small particles were intercepted more frequently than large granules by crowns of *Picea*, but results with *Pinus* were inconsistent (Ekberg and Friberg 1972). The eventual fate of the intercepted fertilizer is unclear, but some is washed down by rain (Mahendrappa 1976), and part is presumably displaced by wind. For urea, volatilization might occur from particles held in tree crowns, but the extent of such losses is unknown for either large or small granules (Belluschi 1972).

Because the dispersal and interception of fertilizer is significantly affected by particle diameter, the customer should ascertain the size specifications of the product before purchase, to ensure it suits his requirements. After delivery, small quantities of material should be removed from several railcars, using a suitable probe according to a specified sampling technique (Anderson 1970). Each sample, of approximately 1 kg is then passed through standard mesh screens (C-E Tyler Industrial Products 1979)[6] to determine if particle sizes conform to the manufacturer's specifications.

The purchaser must obtain prior agreement with the supplier regarding the fate of shipments that contain too much dust or an unsatisfactory proportion of small granules; such material might be accepted at a discounted price (Anderson 1970), or returned for replacement at the manufacturer's expense.

Other Physical Properties

The bulk density of a fertilizer depends upon the specific gravity of individual granules and the number of particles per unit volume. Compared with lighter materials products with greater bulk densities can be spread in wider, more uniform swaths, and are less affected by wind (Amsden 1977). Because the flow of fertilizer through discharge apertures is measured volumetrically, however, dense materials might require very narrow outlets to achieve the correct application rates, and such small openings are difficult to adjust accurately (Amsden 1977). If possible, fertilizers with greater bulk densities should contain smaller concentrations of active ingredients, to ensure a suitably large discharge volume is used to obtain the necessary quantities of plant nutrients. In practice, bulk densities of many commonly used fertilizers are quite similar, and density is often less important than particle size in determining the uniformity of dispersal (Switzer 1972).

Because they have little tendency to fracture, products composed of hard and resilient granules can be transported and spread without adversely affecting particle size. By contrast, material that is soft or brittle can abrade and break during handling, producing small granules and dust. Since pneumatic systems cause excessive particle fracture, mechanical methods such as bucket or belt conveyors, augers and gravity feed must be used to transfer bulk material from railcars to other transportation (Olson 1972, Strand et al. 1973).

Smooth surfaces are essential for unimpeded mass flow (Amsden 1977), and abrasive particles that scratch the spreading equipment could eventually cause unsatisfactory fertilizer dispersal. Wet material tends to form lumps, which can clog the spreader and result in very irregular distribution; railcars containing wet fertilizer should be returned to the supplier, and dry products should receive adequate storage after unloading to ensure no moisture is absorbed.

APPLICATION PROCEDURES

Application Rate

Swath width and uniformity of fertilizer dispersal are sometimes significantly related to quantity of material applied. A Simplex-type apparatus spread 90 kg/ha of forestry grade urea in a swath 33 m wide, but attempts to deposit 180 kg/ha, using the widest possible discharge aperture, produced an average swath width of only 27 m, and the resulting application rate was less than intended.[4] When the flow rate of large urea particles was increased from 6 kg/sec to 10 kg/sec, the width of swath spread by an impeller was reduced from 37 to 24 m, and distribution of fertilizer was more variable (Switzer 1972).

Similar examples of apparent equipment overloading are also encountered with venturi-type spreaders, especially if application rate exceeds 280 kg/ha or mass flow from the aircraft hopper is faster than 16 kg/sec (Yates et al. 1970). A ducted-style spreader delivered a swath width of 11 m when applying 110 kg/ha of fertilizer, but at rates of 340 kg/ha and 560 kg/ha the extent of coverage was reduced to 8 and 5 m, respectively, and dispersal pattern was less satisfactory in the narrower swaths (Akesson and Yates 1962). A corresponding trend occurred when application from a tetrahedron apparatus was increased from 36 kg/ha to 200 kg/ha (Trayford and Taylor 1976). By contrast, Armson (1972) showed variability in urea dispersal was greater at 124 kg/ha compared with 194 kg/ha, when venturi equipment was used.

For each type of spreader and fertilizer, tests must be conducted before operations commence to determine if the required application rate can be delivered uniformly in a swath of suitable width. These tests, which have been used with helicopter[3,4] and fixed-wing (White 1956) projects involve arranging containers of known surface area in a systematic rectangular grid; the extent of the short axis slightly exceeds the predicted swath width, and the longitudinal dimension approximates the expected distance covered by one load of material.

Trials are conducted on open land to exclude interception and deflection of fertilizer by trees. The pilot selects an airspeed and altitude that coincide with those nromally used during an operation; he then aligns on the central long axis of the grid, begins to release fertilizer just before reaching the first row of containers, and continues on a straight course until all material has been expended. Swath width is measured, and fertilizer in each container is weighed to determine application rate and uniformity of dispersal. If the spreader cannot be adjusted to produce a satisfactory coverage with a single pass, an appropriate overlapping pattern must be adopted that allows only a portion of the required quantity of fertilizer to be delivered on each flight.

Flight Pattern

Accuracy of fertilizer distribution might be enhanced if one-half the required amount is applied in each pass, and each line is flown twice; however, Ballard and Will (1971) obtained unsatisfactory coverage with this method, and suggested pilot error was similar for the two passes because the same landmarks were used for alignment. A better procedure involves spreading at half the desired rate, accompanied by a 50% successive swath overlap (Brown 1972, Crown 1974, Mahendrappa 1976).

Further improvement can probably be achieved if only one-third the specified rate is distributed, using a pattern of two-thirds overlap (Strand 1979), but sufficient uniformity is not always obtained by this system.[2] Cross-flying is sometimes considered preferable to lap-flying (Anderson 1970, Edwards 1977), although Bergland (1971) suggested either method could give satisfactory results, and at least one applicator favors the triple-overlap procedure.[9] Cross-flying is often unfeasible in mountainous topography (Strand et al. 1973), or under adverse wind conditions (Eilert 1967), and is sometimes unsuitable because of block size and shape, or the need to avoid ecologically sensitive areas.

Flight Control

The pilot's ability to maintain parallel, equidistant flight lines is a major factor determining the uniformity of fertilizer application (Ballard and Will 1971). When flying is inaccurate, parts of the unit are left untreated, or receive inadequate amounts of material, while other portions of the block are fertilized too heavily. In many operations, the pilot visually estimates the distance between successive swaths, relying on natural features of the stand and topography to guide his progress across the block; this procedure can result in irregular distribution of fertilizer.[5]

To assist the applicator obtain a satisfactory flight pattern, the customer must provide large-scale (e.g., 1:100,000) aerial photographs showing the outline of the treatment unit and positions of ground markers. In addition, the position of every fifth flight line can be indicated (Evans 1972) or the extent of each ten-load portion of the block might be delineated (Crown 1974). A better method for ensuring accurate flight involves locating a person equipped with flags (White 1956, Holmes and Cousins 1960, Davies 1967, Mannion 1977), helium-filled balloons[10] (Armson 1972), or flares (Clark 1968) at each end of the treatment unit, where positions of every swath have previously been marked.

As work progresses, each individual moves to the appropriate ground position, from which his signal is visible for the pilot's guidance. These field personnel must maintain mutual radio contact to synchronize their movements, and should preferably be able to communicate directly with the applicator to

9. R. Kvamme, Helijet Corp., Eugene, Oreg.

10. F. T. Leslie, 1975. Operational fertilization report, Courtenay Division. *In* Aerial fertilization, T.F.L. No. 2, 1975, Project 2-007, 9 p. Crown Zellerbach Can. Ltd. Unpubl. Rep.

permit efficient operational continuity. Field marking of flight lines is greatly appreciated by the pilot[11] and significantly improves the uniformity of fertilizer dispersal;[10] however, such procedures are limited to accessible areas (Ballard and Will 1971), and to open stands in which the markers are conspicuous from the air.

Use of electronic navigation equipment might assist accurate flight, resulting in a more satisfactory aerial distribution of fertilizer. Navigation systems of potential suitability consist of sophisticated instruments in the aircraft, which receive, compute, and display information provided by two portable transponders in the field. Ihis equipment allows the pilot to set successive courses corresponding to the required swath lines, and a steering indicator shows whether correct flight paths are being followed.

An additional feature permits relocation of any position along a particular swath, in case fertilizer is expended before completion of a pass. Tests with two basically similar navigation systems in fixed-wing aircraft showed no improvement in uniformity of fertilizer dispersal, compared with an operation using visual flight control.[12] Wind conditions apparently prevented accurate flying, and drifting of fertilizer presumably contributed to unsatisfactory results.

A helicopter equipped with navigation instruments and a Simplex-type bucket applied fertilizer more evenly than the fixed-wing aircraft;[13] however, since no comparable test was conducted with a visually flown helicopter, the precise benefits of navigation could not be determined for the rotary-wing operation. The need is suggested for additional, carefully controlled trials to study quantitatively whether accurate navigation can enhance the aerial distribution of fertilizer, and if the magnitude of such improvements is related to weather conditions and pilot experience.

Flying Altitude

Pilot safety principally determines the height from which fertilizer is dispersed, with greater altitudes being maintained over steep or irregularly contoured land, and above stands having uneven canopies. Helicopters usually fly at 15–30 m above the trees (Anderson 1970); but one operator uses a clearance of only 9 m (Vineyard 1972), and our applicator in British Columbia sometimes prefers a height of approximately 60 m from the canopy. Fixed-wing aircraft generally spread fertilizer from a distance of 15–60 m above treetops (Clark 1968), with a maximum recommended height of 90 m (Crown 1974).

Optimum flying height required to obtain the widest swath depends theoretically upon airspeed, physical properties of the fertilizer, and velocity with which particles are ejected from the spreader (Yates et al. 1970). In practice, fertilizer spread from a Simplex-type bucket only 6 m above the canopy did not achieve maximum swath width, but an altitude of 30 m was considered suitable.[4] A fixed-wing aircraft with venturi-type equipment produced a very irregular dispersal of fertilizer while flying 3 m above a field, and altitudes of 9–15 m were required to obtain a more satisfactory coverage (Akesson and Yates 1962). To minimize drift, fertilizer should be released close to the canopy[8] (Vineyard 1972), provided safety margins are adequate and a suitable swath width is attained.

Airspeed

Helicopters normally fly at 55–70 km/hr when spreading fertilizer (Anderson 1970, Switzer 1972) although greater airspeeds of 90–110 km/hr are sometimes preferred;[4] fixed-wing aircraft generally operate at even faster speeds of 130–160 km/hr (White 1956, Clark 1968, Armson 1972, Switzer 1972). Because impeller-type distributors used with helicopters are designed to maintain a constant flow of fertilizer, application rate varies inversely with airspeed (Switzer 1972). For fixed-wing aircraft equipped with venturi spreaders, theoretical computations using ballistics data for individual particles suggested swath width decreased at greater airspeeds (Yates et al. 1970). Amsden (1977), however, regarded these calculations based on single granules as inapplicable, and considered a fluent stream of material would attain a wider swath as the plane flew faster. Operational tests are unavailable to confirm either hypothesis, but the need is indicated for maintaining a constant airspeed to achieve correct application rate and a consistent coverage of fertilizer.

WEATHER

Wind

Wind is the most significant weather factor that influences aerial distribution of fertilizer, and calm conditions seldom exist in mountainous, forested terrain. Although flying usually ceases when winds are strong, gusting, or both (Clark 1968), some helicopter (Belluschi 1972) and fixed-wing (Switzer 1972) operations have been conducted in winds of 25–30 kg/hr. Winds affect the pilot's ability to keep a straight course, resulting in uneven or nonparallel swaths (Switzer 1972). In addition, strong crosswinds can cause material to drift, especially if released from 6 m or more above the trees,[8] but winds blowing parallel to flight paths have little effect on uniformity of fertilizer dispersal (Switzer 1972).

When a helicopter was used to spread urea from a height of 30 m, the extent of drifting reached 25 m in crosswinds of 22 km/hr, and displacements of 5–14 m were common in winds of 6–16 km/hr,[4] similar observations were made for operations involving fixed-wing aircraft (Switzer 1972, Mannion 1977).

11. J. Evans, 1975. Report on forest fertilization for Crown Zellerbach Canada Limited Nov. 1975. *In* Aerial fertilization, T.F.L. No. 2, 1975, Project 2-007, 2 p., illus. Crown Zellerbach Can. Ltd. Unpubl. Rep.

12. F. T. Leslie, 1978. Analysis of navigation systems in operational forest fertilization. 19 p. Crown Zellerbach Can. Ltd. Unpubl. Rep.

13. F. T. Leslie, 1978. Analysis of navigation systems in operational forest fertilization. Test II—helicopter application. 6 p. Crown Zellerbach Can. Ltd. Unpubl. Rep.

While the applicator can best judge the *safety* of wind conditions, his customer must insist on postponing operations if distribution of material is shown to be unsatisfactory, and an appropriate contract clause will guarantee the client's prerogative.

Visibility

Poor visibility, caused by mist or low cloud, makes accurate flying difficult, especially without navigation equipment. This can result in nonparallel swaths, incorrect distances between successive flight paths, and imprecise swath length. Rain also reduces visibility, and in coastal British Columbia autumn precipitation is frequently accompanied by cloud descent to treetop level. Applicators using helicopters consider fertilizer can be spread in light rain, provided visibility is adequate; in such circumstances the material must be dispersed from the bucket immediately after loading, to ensure it does not become wet and clog the impeller. Although *safety* conditions involving rain and poor visibility must be determined by the pilot, concerns regarding uniform fertilizer coverage can be minimized if a suitable contract clause permits the client to postpone flying at his discretion.

Snow

Fertilizing is rarely conducted during actual snowfall, but application to snow-covered stands is frequently feasible for the contractor. Trees heavily laden with snow can intercept a large proportion of the applied fertilizer,[2] which presumably does not reach the ground until the snow melts or winds occur. Additionally, fertilizer spread on snow-covered soil might be removed from the site by surface runoff or rapid leaching during spring thaw.[14]

Because snow cover can affect the fate of applied fertilizer, contracts should specify the customer's authority to postpone operations if he considers snow conditions are unsuitable. It is recommended that fertilizer should not be applied to snow depths greater than 15 cm, especially if the soil is frozen, when slopes are steeper than 30%, or both. Cooperative studies are currently being conducted by staff of the Canadian Forestry Service and the British Columbia Ministry of Forests to determine more precisely the conditions under which nitrogenous fertilizers can be reliably spread on snow.

PILOT ABILITY AND EXPERIENCE

Uniform application of fertilizer requires skilled and conscientious pilot consistently capable of accurate flying in adverse topographic and climatic conditions. Inexperienced and inattentive applicators are unlikely to achieve parallel, equidistant flight lines and precise swath lengths, especially without navigation equipment; inadequately trained personnel might also be unable to maintain constant altitude and airspeed in undulating terrain. Pilot proficiency can be determined according to total hours flying experience, including amount of time spent fertilizing or spraying in mountainous forested areas (Belluschi 1972).

In addition, applicators should have sufficient expertise in operating the particular weight class, make, and model of machine that will be used in each project. Inexperienced personnel must be taught by pilots having at least 2 yr participation in forest fertilizing, and trainees should be instructed and observed throughout their first season of application (Olson 1972). Before operations commence, the customer should obtain a full résumé of each pilot's experience, to ensure the contractor provides properly qualified personnel.

14. V. G. Marshall, J. A. Dangerfield, E. Hetherington, and P. C. Pang, 1979. A Problem analysis of the application of urea fertilizer to snow-covered forest soil. 15 p. Environ. Can. Can. For. Serv. Pac. For. Res. Cent. Victoria, B.C. Unpubl. Rep.

CONCLUSIONS

When helicopters and fixed-wing aircraft are used to disperse fertilizer, uniformity of coverage depends predominantly on pilot experience, flying accuracy, and particle size of the material being applied. In addition, spreading equipment must be designed to deliver consistently the correct quantity of fertilizer in a swath of suitable width, and treatment units should preferably be large rectangular or square blocks to simplify flight procedures. Adverse weather can also cause unsatisfactory distribution of material, especially in mountainous terrain where strong winds and poor visibility often occur during autumn operations.

Several factors that affect fertilizer distribution are interrelated. For example, the extent of drifting caused by crosswinds varies with particle diameter and height from which material is dispersed,[8] while the influence of granule size on swath width depends upon airspeed, flying height, and velocity of fertilizer ejection from the spreader (Yates et al. 1970). Furthermore, choice of flight pattern might be determined by size, shape, and topography of treatment areas, and the pilot's ability to maintain constant altitude and speed is often related to contour features.

Because there are many possible reasons for unsatisfactory dispersal of material, cooperative trials are required to assess the performance of the pilot and his equipment in several topographic and climatic conditions, with various flight procedures, using fertilizers having differing physical properties. Aviation engineers are best qualified to ensure correct design of spreading apparatus, and to study aerodynamic properties of solid particles, while fertilizer manufacturers must recognize their customers' requirements and develop suitable new products if necessary.

Foresters and applicators should collaborate to establish adequate procedures for arrangement of treatment units, and to provide accurate methods of flight control using ground personnel or navigation systems. Finally, researchers must relate tree growth to amount of fertilizer applied, explain the silvicultural implications of inconsistent coverage, and define standards for aerial distribution that are feasible for the operator and acceptable to the forest manager.

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