Integrating Technologies to Optimize Aerial Herbicide Applications in Canadian Forest Vegetation Management

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Introduction

Sustainable use of high value fibre derived from Canadian forests is critically dependent upon effective and efficient regeneration. During the earliest phase of these regeneration programs, control of competing vegetation is necessary to ensure stand establishment and mitigate significant growth losses resulting from competition for light, moisture, nutrients and space. Control of competing vegetation is particularly important on richer sites which have the greatest yield potential and are therefore key to long term sustainability. Vegetation control is also important for ensuring replacement of conifer-dominated stands which have been disproportionately reduced through harvesting particularly in the boreal forest landscape of Ontario (Hearndon et al. 1992; Jackson et al. 2000).

A variety of vegetation management tools and techniques (e.g. motor-manual, mechanical, silvicultural, chemical and biological) are available for control of competing vegetation (Thompson and Pitt, 2003). Contrary to general perception, these techniques are routinely employed by Canadian foresters in spatially or temporally integrated strategies and in accordance with site-specific prescriptions (Wagner 1994). Among these various techniques, aerial herbicide treatments are arguably the most effective and efficient approach for controlling complex mixtures of herbaceous and woody competitor species (OFIA/OLMA 1987). Herbicide applications have been a key element in forest management in North America for more than 60 years and continued use is anticipated to meet increasing demands for fibre supply on a diminishing productive forest land base (Wagner et al. 2004).

In Canada, herbicide applications continue to be the dominant technique to ensure successful forest regeneration in the provinces of Ontario, New Brunswick and Alberta where average area treated annually was 19, 25 and 72 thousand hectares respectively through the decade 1994-2004 (NFDP, 2007). Nationally, herbicide use patterns are strongly dominated by a single product – glyphosate, which on average over the last 5 years, was applied to more than 94% of the treated area. Owing largely to the remote location and poor access to many forest sites, aerial application using either rotary or fixed-wing aircraft is the most common method of treatment. In Ontario, which accounts for the majority (49%) of forest herbicide use nationally, loss of aerial herbicide application capability has been estimated as leading to a 4-fold increase in tending costs and 40% reduction in treatments to the productive forest land base (Wagner, 1992). Numerous scientific reviews support the use of glyphosate herbicide as an environmentally acceptable method of weed control (USEPA 1993; WHO 1994; Giesy et al. 2000; Solomon and Thompson 2003; Sullivan 1998; Tatum, 2004).

Notwithstanding operational importance, cost-effectiveness and general environmental acceptability of herbicide use in Canadian forest management, continuous improvement in best management practices and associated technologies is required to address concerns and demands of the public land owners, forest certification agencies and industry accountants. The overarching goals for improvement are optimized targeting for silvicultural cost-effectiveness and minimization of potential environmental effects (Campbell and Howard, 1993). Detailed discussion of aerial spray applications in forestry and associated technologies have been previously published (Picot and Kristmanson, 1997; Payne 1998). In recent years substantial developments in a variety of new technologies including differential global positioning systems (DGPS), geographic information systems (GIS), electronic guidance systems, automated booms and remote sensing have occurred, all of which have potential to enhance aerial herbicide applications. While all of these technologies are used to varying degrees by forest managers and aerial herbicide applicators, full integration in both concept and practice has generally been lacking.

This study was undertaken to assess the potential for integrating a suite of modern technologies with a view to optimizing efficacy, cost-effectiveness, environmental protection and post-spray monitoring of aerial herbicide applications. The project focused on case studies of operational aerial herbicide applications made with a fixed-wing aircraft to spray blocks typical of Northern Ontario. Specific objectives were to:

(a) Evaluate the potential use of electronic guidance and automatic control of spray booms
(b) Assess the uniformity of herbicide deposition on target and depositional patterns about artificial exclusion zones
(c) Compare ground based DGPS tracking, digital and near-infrared satellite image analysis as methods for defining phytotoxicity contours
(d) Assess the potential to realize silvicultural exclusion zones within operational spray blocks

For the purposes of this paper, silvicultural exclusion zones are defined as areas within the spray block which do not require herbicide treatment to meet silvicultural objectives. These might include non-stocked areas, areas of exposed bedrock, areas with advanced natural regeneration or areas which have insufficient competition to warrant herbicide treatment.

Materials and Methods

Experimental Site Characteristics

All experimental applications were made to forest regeneration sites within the Gordon Cosens forest near Kapuskasing Ontario. This portion of the boreal forest region is comprised principally of black spruce (*Picea mariana* (Mill.)) and balsam poplar (*Populus balsamifera* L.) as the dominant softwood and hardwood species. Following harvesting, these highly fertile sites are typically inundated with a wide variety of invasive pioneer species forming a plant community which competes aggressively with transplanted seedlings for light, nutrients moisture and growing space. Key competitor species include red raspberry (*Rubus idaeus* L. var. strigosus (Michx.)), various grasses including *Calamagrostis canadensis*, alders (*Alnus crispa* - (Ait.) Pursh - Betulaceae & Alnus rugosa - (DuRoi) Spreng), trembling aspen (*Populus tremuloides* Michx.), large-leaved aster (*Aster macrophyllus* L) and mountain maple (*Acer spicatum* Lam).

Experimental sites were selected from those designated for operational aerial herbicide application treatments based on several criteria including representative spray block size, competing vegetation cover and uniformity, an obvious preferred flight-path orientation and road accessibility. Specific characteristics and timing of applications for each experimental site are provided in Table 1. Each of the spray blocks were delineated by a process combining rectification of 23 x 23 cm black and white supplemental aerial photographs, with Ontario base map water and harvest area layers using ArcGIS software (ESRI, Redlands, California) and the NAD83 datum.

Within each of the experimental spray blocks an artificial exclusion zone was established as a rectangle. The UTM coordinates for the four corner point positions of each artificial exclusion zone were established using a ground-based DGPS unit (Garmin GPS 76 equipped with GA29F antenna for WAAS; Garmin GPS76, Garmin Olathe, KS, USA). With the antenna held at approximately 3 m a above ground level and averaging over a period of 3 minutes the estimated positional accuracy was approximately 4 m, which compares favourably with accuracy estimates for other DGPS systems (Tortosa and Beach, 1995). GIS shape files for the spray block as well as DGPS coordinates for the exclusion zone boundaries were subsequently integrated into NO1 files used to control applications to individual spray blocks.

Aerial Applications & Electronic Guidance

Aerial applications were made using a fixed-wing aircraft (Grumman AgCat G-164A, C-GQHQ, General Airspray Inc. Lucan, Ontario) equipped with a wide-area-augmentation system (WAAS) enabled GPS receiver, an AG-NAV2 electronic guidance system (AG-NAV Inc, Newmarket, Ontario). The dispersal system was configured with pneumatically controlled spray boom valves and a total of 31 D6-46 nozzles oriented straight back on drop pipes 38 cm below the lower wing. Preliminary experiments were conducted to define settings for system, electronic and hydraulic lag times which were programmed into the electronic guidance system as offsets to maximize the accuracy in relation to automated control of spray booms via the electronic guidance system. All applications were made by an experienced spray pilot (Paul Hodgins, General Airspray Inc., Lucan Ontario). Glyphosate herbicide (Vision®, Monsanto Canada Inc.) was mixed with water and applied in each case at rates of either 2.5 or 1.9 kg acid equivalent (a.e.) per ha, in a total volume of 17 L/ha. The calibrated swath width was 20 m at an application pressure of 158.6 kPa. Electronic guidance system data were output as text files and uploaded to a spreadsheet to allow for calculation of means and variation of aircraft flight speed, altitude and azimuth during the period when booms were on over each spray block. Release height was calculated as the differential in mean aircraft height and altitude values available from ground based DGPS locations on the spray block. Timing of initiation and completion of spray applications to the each block and exclusion zone were also calculated based on electronic guidance system outputs.

Meteorological Monitoring

Critical meteorological conditions of air temperature, relative humidity, wind speed and wind direction were monitored continuously throughout each spray session. Air temperature and relative humidity were obtained using a Campbell scientific model 207 shielded probe held at 13 m above ground level. Wind speed and direction were measured using an R.M. Young anemometer. Rainfall was monitored using a tipping bucket rain gauge. Data from all probes and instruments were recorded every 5 seconds using a CR10 datalogger and LoggerNet Version 3.1.2 software (Campbell Scientific Corp, Edmonton, AL). Data were then averaged over the spray session to characterize average conditions during applications to the entire block. Temperature, humidity and wind conditions were monitored using probes held at 13 m above ground level. Summary details of meteorological conditions during experimental spray applications are provided in Table 2.

Herbicide Deposition

Herbicide deposition both within the target area and through artificial exclusion zones was monitored using artificial deposit collectors positioned along 5 transects oriented parallel to the flight lines. A generalized schematic representation of the sampling transect layout is provided in Fig. 1. Intervals between transects and spacing of collectors along each transect varied with site, but were typically 50 m and 15 m respectively. One-half of the total collectors were deployed within the artificial exclusion zone with an equal number deployed on either side of the exclusion zone where full herbicide depositions was anticipated (on-target area). Mean deposition within exclusion and on-target areas were based on approximately 50 subsamples each, but varied with setup and in some cases owing to destructive loss or contamination of collectors in the field. The actual number of samples used to calculate deposition means in each case are provided in Table 3. Deposit collectors were constructed from glass fibre paper (98 cm^2) stretched flat in balsa wood frames at a height ~ 2 m above ground, just above the average brush canopy, by attachment to two parallel high tension nylon lines supported every 75 m with aluminum support poles. Deposit collectors were typically deployed within each block 1 day prior to spray application and picked-up between 1 and 6 hrs post-treatment. No chemical deposition or meteorological data were collected for spray block 66, while on-target and exclusion zone deposition estimates for block 65 were based on substantially fewer point samples (n=38 and n=22, respectively) owing to a storm event prior to treatment which destroyed a number of artificial collectors on transects 4 and 5.

Quantitative analysis of glyphosate deposition (total µg glyphosate/collector) was conducted using a gas chromatographic technique with nitrogen-phosphorous detection similar to that described previously (Thompson et al. 2004). Based on analysis of numerous (n=83) quality control samples involving glass fibre paper samples fortified with known amounts of glyphosate and AMPA and analyzed concurrently with field samples, overall recovery efficiencies and precision estimates (coefficient of variation (CV)) for this method were 85.08 (9.1%) and 74.34 (13.4%) respectively. Deposit data were normalized to account for differences in application rate and slight variances in artificial collector sizes used in 2002 as compared to 2003.

Estimation of Phytotoxicity Contour, Incursions and Silvicultural Exclusion Zone Areas

Phytotoxicity contours, defined as the visible boundary between live and dead competing vegetation were determined approximately one year after herbicide application. Delineation of phytotoxicity contours involved three different estimation procedures including ground-based DGPS tracking, digital image analysis or near infra-red satellite image analysis. For DGPS tracking, contours were delineated by an individual walking the live/dead vegetation boundary while collecting track data at 10 m intervals on a hand-held differential global positioning system (DGPS) equipped with an external antenna held approximately 3 m above ground level as described above. For image analysis techniques, contours were delineated by drawing a line differentiating contiguous green versus brown pixels in true-colour digital imagery or pink versus aqua-marine pixels in near-infrared satellite images. All images used for these analyses were captured approximately one year post herbicide treatment and ortho-rectified based on 6 to 8 points for which accurate DGPS coordinates had been obtained. Ortho-rectification points were comprised of nearby road intersections, bridges and landings as well as a minimum of 4 specific positions marked with white cloth strips (4 m x 1 m) to form an X shape. All ortho-rectification points were visible in both digital and satellite images. Multi-spectral satellite images covering an area of approximately 16 km^2 encompassing the experimental spray blocks were captured from the high resolution IKONOS satellite (Space Imaging, Thornton, CO). The resultant multispectral data includes a near-infra-red band that is recognized as a powerful discriminator of reflectance from living vegetation (Gibson, 2003). Satellite images were uploaded and processed using PCI Geomatica Version 9 software (PCI Geomatics Enterprises Inc., Richmond Hill, ON). Processing involved merging data the four separate reflectance bands (red, green, blue and NIR) into a single image, sub-setting the image to focus on the specific experimental blocks of interest and geo-referencing to ortho-rectification points with known coordinates as described above. Digital images of each spray block were captured from fixed-wing or rotary wing aircraft using either a Nikon D50 or a digital camera respectively. True colour digital images were uploaded and processed using Fugawi 3 navigation software (Northport Systems Inc., Toronto ON). Similar applications of low cost, high-resolution digital imagery have previously been described by Haddow et al. (2000).

Phytotoxicity contours as estimated by these three techniques, together with exclusion zone boundary lines, were overlain on ortho-rectified digital or satellite images to estimate incursion distances. Incursion distances were defined as the perpendicular distance between the phytotoxicity contour line and the artificial exclusion boundary, as determined from measurements made relative to 15 evenly spaced points spanning exclusion zone boundaries in each spray block. Mean, minimum, maximum and standard deviation of incursions distances were calculated for each spray block and for all blocks collectively. The silvicultural exclusion areas realized within the artificial exclusion zones for each spray block were determined based on satellite image analysis. Silvicultural exclusion areas were considered as the polygonous area circumscribed by phytotoxicity contours defining live versus dead vegetation as determined using near-infrared satellite image analysis.

Statistical Analysis

Statistical and graphical analyses were performed using SigmaPlot 10.0 2004 version 9.01 software (Systat Software Inc.). Summary statistics (mean, median, standard deviation, coefficient of variation (CV), standard errors, minima, maxima and 95% confidence limits) were calculated for analytical quality control data, upwind and downwind incursion distances and herbicide deposition data for each block. As deposition data did not meet the assumptions of normality, comparisons of median deposits for on-target and exclusion zone deposits within each block were made by Mann-Whitney rank sum tests. Comparisons of herbicide deposition and phytotoxic incursion distances among blocks were made based on Kruskal-Wallis one way analysis of variance on ranks, followed by Dunn's multiple comparison procedure to detect significant differences. The decline trend in mean herbicide deposition with down wind distance from the exclusion zone boundary was modeled using non-linear regression analysis with an exponential decline function of the form $Y= a*\exp(b*X)$. The estimated distance required to yield mean deposition levels equal to 50% of Y-intercept values was calculated as $Y_{50} = -0.693/b$.

Results and Discussion

Experimental Sites

Empirical data were collected for a total of 8 experimental spray blocks. Two preliminary experimental sites were treated with glyphosate (Vision) as a chemical site preparation treatment (2.5 kg a.e./ha) on August 7 and 8, 2002. An additional 6 spray blocks were treated with the same herbicide formulation at a rate of 1.9 kg a.e./ha in 2000. All applications were made using the same fixed-wing aircraft which was equipped with an electronic guidance system and auto-controlled spray booms as described above. Spray block sizes ranged from 42.7 to 133.9 ha with an overall mean of 69.4 ha. Artificial exclusion zones of varying sizes averaging 6 ha were imposed within each spray block. Owing to time, logistical and financial constraints, no deposit or meteorological data were taken for block 66 negating inclusion of this block for herbicide deposition assessments.

Application and Meteorological Parameters

Data characterizing critical application and meteorological parameters for each of the experimental spray blocks involved in this study are provided in Table 2. Parametric sensitivity analysis and modeling studies (Teske and Barry 1993; Teske and Thistle 2003) has previously demonstrated that deposition of similarly sized droplets is influenced in decreasing order of importance by release height, spraying speed, wind direction and wind speed during aerial pesticide applications. The combined effects of relative humidity and air temperature are also important as these are the key determinants of evaporative reduction of droplet size following release (Franz et al. 1998). One of the key advantages of electronic guidance systems is provision of quantitative data characterizing the accuracy and precision for release height and spraying speed variables. Other advantages include detailed information on variation about track spacing and spray booms activity in relation spray block or exclusion boundaries.

The overall average release height was 30 m above ground level, with the mean for any given block ranging from 26 to 36 m a.g.l. Electronic guidance system data showed little variation (CV <2% or 0.5 m) in release height during spray applications within a given spray block. Spraying speed was also very consistent within spray blocks, with < 3% variation in all cases and an overall average spraying speed of 172 km/hr. Mean error in track spacing was +/- 1 meter with a standard deviation of 6 or less, indicates overall accuracy and precision in aircraft positioning relative to prescribed spray swath centers contributing to the generally high degree of uniformity in herbicide deposition within the target zone (Table 3). Slightly greater variation in track spacing was observed for block 62 (STDev = 6).

An example of the AG-NAV2 guidance system graphic output file for spray block 1 is provided, together with the corresponding near-infrared satellite image, in Fig 2a and 2b respectively. The size of the spray block and the artificial exclusion zone are provided in Table 1. The irregularly shaped exclusion in the northern portion of the graphic file (Fig 2a) represents an operationally typical silvicultural exclusion area imposed about a stand of advanced coniferous regeneration, also evident in the satellite image (Fig 2b), which did not require herbicide treatment. The AGNAV2 file demonstrates generally effective control of track spacing with minimum gaps or cross-tracking also evidenced by the mean track error and standard deviation (0 and 2 respectively) observed for this block (Table 2). Even track spacing contributes to uniform herbicide deposition and resultant uniformity of efficacy throughout the spray block. In the near-infrared satellite image (Fig. 2b), uniformly high efficacy is evidenced by mottled aqua-marine colour representing herbicide-killed vegetation which dominates throughout the spray block in contrast with the mottled pink reflectance from living grasses, herbaceous and brushy vegetation in both the artificial exclusion zone and in the surrounding untreated cutover area While electronic guidance systems provide valuable data on aircraft position and spray boom activity, they do not provide information on the actual deposition of the spray cloud. This differential is exemplified by comparing Fig 2a which confirming no direct spray within either the artificial or natural exclusion zones or beyond spray block boundaries and Fig. 2b, which shows phytotoxic effects associated with slight incursions into the northern portion of the artificial exclusion zone and beyond the southern boundary of the spray block as the result of wind from the north.

In Ontario, acceptable meteorological conditions for aerial herbicide applications of glyphosate are: wind speed < 15 km/hr, relative humidity > 50%, air temperature < 25 ^{o}C and no rainfall anticipated within 12 h. Observed meteorological data (Table 2) show that applications to the experimental blocks were made within operationally acceptable conditions with the exception of block 51. In general, the combination of low mean wind speeds (< 6 km/hr), high relative humidity (> 60%) and moderate air temperature (< 18 ^{o}C @ 10-13 m above ground level) would be anticipated to result in good herbicide deposition and resultant efficacy. Low wind speeds were generally correlated with substantial variation in wind direction, as is particularly evident for blocks 61, 62 and 65 where wind directions varied from 0 to > 340 degrees. Such light and variable wind conditions, considered typical of aerial herbicide spray scenarios, are unlikely to result in substantial downwind drift, generating relatively lower magnitude of deposition at distance into the exclusion zone, a more uniform relation of phytotoxicity contours about the exclusion zone boundaries and greater overall percentage of the exclusion zone being realized as an actual silvicultural exclusion. Block 51 represents the relative worst-case scenario for meteorological conditions among experimental spray blocks in this study, with conditions characterized by axial winds with a mean of 5 and gusting to 14 km/hr, low relative humidity averaging 44% and relatively high average air temperatures of 20-22 ^{o}C. These conditions resulted in relatively high mean deposition into the exclusion zone, the greatest phytotoxic incursion distances and lowest area of silvicultural protection within the artificial exclusion zone observed in his study. Despite the negative effects on drift into the exclusion zone, sub-optimal meteorological conditions did not deleteriously affect the level or variation in deposition within the target zone.

Herbicide Deposition

In this study, herbicide deposition was measured quantitatively based on artificial collectors in both the on-target area and within artificial exclusion zones with data subsequently correlated to observations on efficacy within the target zone, as well as phytotoxicity contours and resultant silvicultural exclusion areas realized within each exclusion zone. Mean deposition of glyphosate on artificial collectors located within the on-target zone in all spray blocks are shown in Fig. 3. The combination of effective control over critical application parameters of release height, spraying speed and track spacing resulted in uniform herbicide deposition within the on-target areas as evidenced by the overall average coefficient of variation (53%) (Table 3). This degree of variation is very similar to that (46.5% CV) previously reported for aerial applications made using rotary wing aircraft equipped with hydraulic boom and nozzles (Thompson et al. 1992) . The overall mean deposition across all spray blocks (n= 363) was 1190 ug/collector with a lower 95% confidence limit equivalent to 1098 ug/collector. An analysis of variance on ranks indicated statistically significant differences (p <0.001) in mean on-target deposits among the seven spray blocks as would be expected given the variety of conditions under which they were sprayed (Table 2). Statistical differences in on-target deposition as elucidated by pair-wise multiple comparison tests (p=0.05) are indicated in Fig.3, with the lowest overall deposition occurring on spray blocks 61 and 65. Among the experimental spray blocks monitored in this study blocks 61 and 65 were characterized by lowest on-target deposition and concomitant highest degrees of variation (~69% CV).

Based on the lower 95% confidence limit of 1098 ug/collector deposit estimates and interpolating from previously published deposit-response relationships (Pitt et al. 1992; Thompson et al. 1992), suggests that average deposition within the on-target areas of all spray blocks would be expected to yield essentially complete control of aspen and poplar and approximately 85% control of raspberry, which were the dominant brush and herbaceous species on these sites. Even the significantly lower mean deposition observed for block 65 would yield interpolated efficacy approximating 95% for trembling aspen and poplar and approximately 80% control of raspberry. The levels of efficacy interpolated from these dose-response relationships correspond well with the generally high level of efficacy observed in digital or near-infrared satellite imagery for these spray blocks (see Figs 2b, 6a and 6b).

The overall pattern of herbicide deposition about artificial exclusion zones is typified by results for block 1 (Fig. 4a). In this case the mean (N=60) on target deposit of 1256 ug/collector and a 42 % coefficient of variation which was the lowest observed among experimental spray blocks in this study. We note here that although individual collectors were held just above the average height of the competing vegetation canopy, deposition at any given point in the sampling array may have been influenced by density and roughness of the surrounding vegetation thereby contributing to variation in observed deposits. Deposition into the artificial exclusion zone shows a consistent pattern of exponential decline with distance from the northern (upwind) boundary. This pattern is attributable to finer droplets from the spray cloud drifting into the artificial exclusion zone with near axial winds from the north (5 degrees; range 0-22 degrees). Relatively greater deposition within the exclusion zone as well as anomalous spike on one sample are apparent along the two outermost transects. In this case, the exclusion zone was bounded to the east and west by tertiary skid trails, which are substantially more open, potentially enhancing drift-deposition in these areas. Despite these anomolies, the mean deposition (n=30) at distances of 30 m or more into the exclusion zone was 271 ug/collector representing a small fraction (22%) of the mean on-target deposit . Modeling mean deposition from 10 to 160 m through this exclusion zone showed a statistically significant (p = 0.0001) exponential decline in deposit with down wind distance and an estimated distance to reach 50% deposit levels of 18 m (Fig. 5).

Blocks 5 and 51 represent relative worst case scenarios for herbicide deposition into the exclusion zones (Table 3) with mean deposit levels beyond 30 m approximating 50% of the mean on-target deposit. Correspondingly high phytotoxic incursion distances were also observed for these two blocks as described below. The deposit pattern for Block 51 (Fig. 4b) is characterized by uniformly higher deposition about the southwestern (upwind boundary) but relatively low deposits in the northeastern portion of the exclusion zone. The pattern indicates a relatively greater proportion of the spray cloud being carried further into the exclusion zone with higher winds (mean 5 km/h; gusting to 14 km/hr) from the southwest. Under these conditions, modeling of observed mean deposits with down wind distance also showed a statistically significant (p =0.0001) decline, but with a much lower slope value resulting in an estimated distance to 50% deposit levels of 53 m (Fig. 5).

Remote Sensing, Phytotoxicity Contours and Silvicultural Exclusion Zone Assessments

Phytotoxicity contours, the boundary between live and dead vegetation resulting from herbicide treatments, were determined about artificial exclusion zones using ground-based DGPS tracking, digital and near infra-red satellite image analysis. Phytotoxicity contour lines typically overlapped very closely with one another as exemplified by results for block 65 (Fig. 6).

The distance between the artificial exclusion zone boundary and the phytotoxicity contour line were measured as phytotoxic incursion distances and define the degree of incursion of the depositing spray cloud at levels above phytotoxic thresholds for the competing vegetation complex on the site. As exemplified by the case for block 65 (Fig. 6), phytotoxic incursion distances were greatest along the upwind boundary and minimal or nil about other boundary lines. Overall there was very good agreement in mean incursion distance estimates among the different estimation techniques with satellite image analysis typically generating slightly higher or more conservative estimates. Mean phytotoxic incursion distances for the worst case upwind boundaries in each of the experimental spray blocks are shown in Fig. 7. Based on conservative satellite image analysis, the overall mean (n=93) maximal incursion distance was 59.7 m with an upper 95% confidence limit of 69 m. Omitting data for the worst case block 51, resulted in a mean (n=80) of 45.5 m with an upper 95% confidence limit of 51 m. A Kruskal-Wallis ANOVA on ranks showed a statistically significant difference ($p < 0.0001$) among the maximal median incursion distances for the various cases and subsequent multiple comparisons using Dunn's method isolated statistically significant ($p = 0.05$) differences between specific blocks.

Observed mean maximal distances for phytotoxic incursions were strongly correlated to wind conditions and observed patterns of chemical deposition. For example, blocks 1, 61, and 62, were characterized by light and variable winds with mean wind speeds less than 2 km/hr with gusts < 8 km/hr. All of these blocks showed mean maximal phytotoxic incursion distances < 34 m from their upwind boundaries, corresponding with strong exponential decline patterns of chemical deposition which dropped off dramatically beyond 30 m (see for example Block 1, Fig 4a). In contrast, block 51 which was characterized by the highest mean (5-6 km/hr) and maximal (12-14 km/hr) wind speeds and which was the observed worst case for chemical deposition into the exclusion zone, showed the greatest maximal phytotoxic incursion distance of 147 m. Interpolating from Fig. 5, the mean maximal incursion distances for blocks 1 and 51 suggest a phytotoxicity threshold hold dose between 300 and 700 total ug/collector.

The area of live vegetation bounded by phytotoxicity contours within artificial exclusion zones for which there was comparative data are presented in Table 4. Data for block 5 were excluded from this analysis as maximal incursions into this spray block were not consistent with dominant wind direction and were attributed to leakage of the pneumatic spray boom valves. Results showed that between 73.7 and 79 percent of the artificial exclusion area was in fact protected from a silvicultural perspective depending upon the estimation technique employed. In agreement with the similarity in phytotoxic incursion contours from which they are derived, there was generally very good agreement in silvicultural exclusion area estimates based on the three different estimation techniques. Again, satellite image analysis was the most conservative technique in all cases, yielding silvicultural exclusion zone area estimates approximately 4 to 5% lower than those determined by digital image analysis or ground-based DGPS tracking.

In all cases a small additional area of protected vegetation occurred outside and downwind of the artificial exclusion zone boundary and predominantly on the downwind side as a result of downwind shift of the depositing spray cloud away from the exclusion zone. Based on satellite analysis, the size of this area ranged from 6.5 to 10.2%, suggesting that on average approximately 80% of the living vegetation complex could be protected within exclusion boundaries with the application of an appropriate offset for downwind drift displacement.
Based on the limited empirical data available from this experiment, offsets of approximately 30 m upwind of exclusion zone boundaries would be required to ensure essentially complete silvicultural exclusion under scenarios with mean wind speeds and gusts were below 8 km/hr. Proportionally larger upwind offsets would be required in cases with mean wind speeds and gusts between 8 and 15 km/hr.

Conclusions

Results of this study, which employed a suite of advanced technologies to optimize aerial herbicide applications demonstrated uniform high levels of on-target deposition (Avg 1148 ug/collector with 53% CV) resulting from precise control over release height, spraying speed and consistent track spacing as determined from electronic guidance system data. Electronic guidance data also demonstrated general accuracy in controlling automated booms activity about artificial exclusion zone boundaries. Remote sensing analysis using either true-colour digital or near-infrared satellite imagery confirmed general high levels of efficacy on competing vegetation within spray blocks. Delineation of phytotoxicity contours about exclusion zone boundaries using ground-based DGPS tracking, digital or near-infrared satellite image analysis showed high levels of agreement among the three techniques and excluding one exceptional case (block 51), resulted in a mean phytotoxic incursion distance of 45.5 m with an upper 95% confidence limit of 51 m. Deposition patterns observed from these empirical case studies do not address the full range of multivariate interactions which ultimately control herbicide deposition following aerial release and as such they are an insufficient basis for making operational recommendations. However, in general, chemical deposition and phytotoxic incursion distances as determined here are well within guidelines for 60 m buffer zones to protect environmentally sensitive areas adjacent to spray blocks (Ontario Ministry of the Environment and Energy, 1992).

In this study, silvicultural exclusion as evidenced by general lack of plant mortality one year-post treatment as determined by ground reconnaissance, true-colour digital image analysis and near-infrared satellite image analysis, was effectively achieved in area averaging approximately 75% of the artificial exclusion zone area under typical conditions. Failure to achieve 100% exclusion within the artificial boundary was predominantly associated with wind-assisted drift and deposition of the spray cloud at phytotoxic levels (~ 300 to 700 ug/collector) within 30 m of the upwind exclusion zone boundary. Incursion distances and resultant area of silvicultural protection were correlated to general meteorological conditions. In the exceptional case a combination of sub-optimal conditions including axial winds with a mean of 5 and gusting to 14 km/hr, low relative humidity averaging 44% and relatively high average air temperatures of 20-22 ^{o}C resulted in a mean incursion of 147 m and only 18% of the area being protected from phytotoxic levels of deposition. In order to achieve a higher percentage of protected area, upwind offsets proportional to wind speed are required where mean wind speed and gusts exceed thresholds of approximately 5 and 8 km/hr respectively. Recent development of aircraft-mounted monitoring systems such as the AIMMS-20AG (Aventech undated, Aventech Inc, Barrie, Ontario) may provide an operationally feasible means of acquiring, recording and integrating meteorological data with spray application data to facilitate such adjustments using either auto-booms or conventional methods of application. However, further research is required to demonstrate feasibility of this approach under operational conditions relevant to forest herbicide use scenarios.

Many Canadian forestry companies use geographic information and global positioning systems extensively in their general operations thus serving as a solid practical basis for integration of other technologies including DGPS, electronic guidance, remote sensing and automated booms. While each of these technologies provide their own advantages when used independently, the fully integrated suite of technologies provides a means of fully optimizing the planning, conduct and post-treatment monitoring of aerial herbicide application programs. Conceptually this approach would start at the harvest stage GIS and DGPS technologies to plan and accurately map potential spray blocks and silvicultural exclusion zones. In this step, collection of high quality DGPS data at several points throughout or proximal to the spray block, which are discernable in aerial photography or satellite imagery and which accurately delineate planned silvicultural exclusions or buffer zones is a critical requirement. High quality site-specific DGPS data can be subsequently used to enhance the accuracy of GIS-based maps, ensure accuracy of derivate shape files uploaded in the electronic guidance system and as a basis for ortho-rectification of digital or satellite images for remote sensing analysis post-treatment. Accurate shape files, concordance of datum and position estimates between the aircraft and the electronic data files are considered pre-requisites to full and effective use of electronic guidance systems. If used in conjunction with automated-booms, preliminary calibration work must be done with each individual aircraft to ensure appropriate electronic and hydraulic lag times. As demonstrated in this study, electronic guidance systems allow for effective control over track spacing and uniformity of the spray application and reduce reliance on physiographic boundaries thereby allowing for treatment of partial or exclusion of areas not requiring treatment to meet silvicultural objectives. This capability would result in proportional reductions in total herbicide load to the environment as well as reduced chemical costs to the overall operation. Electronic guidance system data files provide a detailed archival record of aircraft position, release height and spray boom activity, as well as several other application parameters which are not otherwise achievable. These data can be utilized as a post-treatment quality check to confirm effective coverage of the spray block and accuracy of the application relative to boundaries and exclusion zones. The data also have additional value in terms of pilot training and as source data for aerial dispersal modeling. Remote sensing, using either true-colour digital or near infra-red satellite imagery, provides a powerful method of post-treatment assessment. In combination with site-specific DGPS data for ortho-rectification and commercially available image analysis software, the area receiving efficacious treatment, phytotoxicity contour delineation and areas of actual silvicultural exclusion can be accurately estimates.

In combination the suite of GIS, DGPS, electronic guidance, meteorological monitoring and remote sensing technologies as described in this paper provide for full characterization of application and meteorological variables influencing deposition of herbicide sprays and a method for post-treatment assessment of phytotoxic effects. With appropriate precautions for assurance of data quality and system control, these technologies can be used to optimize aerial herbicide applications for maximal efficacy and minimal environmental risk. Full integration of these technologies together with dispersal models such as AGDISP (Bilanin et al. 1989; Bird et al. 2002; Teske and Thistle 2003) and dose-response models on a GIS-based platform would greatly facilitate general operational use. A decision support system (SprayAdvisor) with these capabilities is currently being developed (Strager, J.M. 2004) and validated for use in Canadian forest herbicide application scenarios (Thompson et al. 2007). Once validated, the decision support system should provide a means for integrating case-specific data with extensive scientific and technical knowledge to make spatially explicit predictions of herbicide deposit and effect under a wide variety of use scenarios. The decision support system is also anticipated to have added benefits in terms of technology transfer and training for aerial applicators and forest managers, and in demonstrating and encouraging operational best practices for aerial herbicide applications in Canadian forestry.

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References:

Aventech (undated). AIMMS-20AG. Aircraft integrated meteorological measurement system. Available from http://www.aventech.com/pdf/AIMMS-20AG_revNov05.pdf. Pp. 2. [accessed 22-March 2007].

Bilanin, A.J.,m Teske, M.E., Barry, J.W. and Ekblad, R.B. 1989. AGDISP: the aircraft spray dispersion model, code development and experimental validation. Transactions of the ASAE. **32**: 327-334.

Bird S.L., S.G. Perry, S.L. Ray, and M.E. Teske. 2002. Evaluation of the AGDISP Aerial Spray Algorithms in the AgDRIFT Model. Environ. Tox. Chem. **21**:672-681.

Campbell, R.A. and Howard, C.. 1993. Priorities for forestry herbicide application technology research. Can. J. For. Res. **23**: 2204-2212.

Gibson, L. 2003. Finding Road Networks in IKONOS Satellite Imagery. Proceedings of ASPRS 2003 Conference, Anchorage, Alaska, May 5-9, 2003.

Giesy, J. P., Dobson, S., and Solomon, K.R.. 2000. Ecotoxicological risk assessment for Roundup herbicide. Review of Contamination and Toxicology **167**:35–120.

Haddow, K.A., King, D.J., Pouliot, D.A., Pitt, D.G., Bell, F.W., and Hall, R.J. 2000. Early regeneration conifer identification and competition cover assessment using airborne digital camera imagery. For. Chron. **76**: 915-928.

Hearndon, K.W., Millson, S.V., and Wilson, W.C. 1992. A report on the status of forest regeneration. Queens' Printer for Ontario, Ontario, Canada.

Jackson, S.M., Pinto, F., Malcom, J.R. and Wilson, E.R. 2000. A comparison of pre-European settlement (1857) and current (1981-1995) forest composition in central Ontario. Can J. For. Res. **30**: 605-612.

NFDP 2007. National Forestry Database Program [online]. Available from http://nfdp.ccfm.org/ [accessed 22March 2007].

OFIA/OLMA. 1987. Tending and protection of the timber resource. Ontario Forest Industries Association and the Ontario Lumber Manufacturers Association (Panel 7) Statement of Evidence to the Ontario Class Environmental Assessment Board. pp. 210

Ontario Ministry of Environment and Energy. 1992. Ontario Ministry of Environment and Energy buffer zone guidelines for aerial application of pesticides in crown forests of Ontario. February, 1992. pp. 5 including appendices.

Payne, N.J. 1998. Developments in aerial pesticide application methods for forestry. Crop Protection. **17**: 171-186.

Picot, J.J.C. and Kristmanson, D.D. 1997. Forestry pesticide aerial spraying : spray droplet generation, dispersion, and deposition. pp. 213.

Pitt, D.G., Flemming, R.A., Thompson, D.G., and Kettela. E.G. 1992. Glyphosate efficacy on eastern Canadian forest weeds. Part II: Deposit-response relationships and crop tolerance. Can. J. For. Res. **22**: 1160-1171.

Solomon, K. R., and Thompson, D.G.. 2003. Ecological risk assessment for aquatic organisms from over-water uses of glyphosate. Journal of Toxicology and Environmental Health, Part B. **6**:289–324.

Strager, J.M. 2004. Spray Advisor ArcView Extension. Version 1.0. Manual Last Modified: April 5, 2004. pp. 23.

Sullivan, T.P., Wagner, R.G., Pitt, D.G. 1998. Changes in diversity of plant and small mammal communities after herbicide application in sub-boreal spruce forest. Can. J. For. Res.. **28:** 168-177.

Tatum, V.L. 2004. Toxicity, transport and fate of forest herbicides. Wildlife Society Bulletin. **32**: 1042-1048.

Tortosa, D. and Beach, P. 1995. Accuracy and Precision Tests using Differential GPS for Natural Resource Applications. Northern Ontario Development Agreement, Northern Forestry Program, NODANOTE #18. pp. 11. [online]. Available from http://hosting.soonet.ca/eliris/gpsgis/acuracy.htm.. [accessed 22-March 2007].

Teske, M.E. and Barry, J.W. 1993. Parametric sensitivity in aerial application. Transactions of the American Society of Agricultural Engineers, **36**: 27-33.

Teske, M.E. and Thistle, H.W. 2003. Release height and far-field limits of Lagrangian aerial spray models. Transactions of the ASAE. **46**: 977-983.

Thompson, D.G., Pitt, D.G., Fleming, R.A. and Kettela, E.G. 1992. Glyphosate efficacy on eastern Canadian forest weeds. Part I: Experimental design and on-target deposit. Can. J. For. Res. **22**:1151-1159.

Thompson, D.G.. Thistle, H. and Richardson, B. 2007. Development, Validation and Application of SprayAdvisor as a Decision Support System for Optimizing Aerial Herbicide Spray Programs. Extended Abstract . Proceedings of the the Spray Efficacy Research Group – International Workshop, Banff, Alberta, February 13-17, 2006. pp. 5.

USEPA 1993. U.S. Environmental Protection Agency R. E. D. facts: glyphosate. PA-739-F-93–011. U.S. Environmental Protection Agency, Washington, D.C., USA.

Wagner, R. 1992. Survey of impacts resulting from herbicide restrictions. The VMAP Report **1**:6-7.

Wagner, 1994. Towards integrated forest vegetation management. J. For. **92**:26-30.

Wagner, R.G., Newton, M., Cole, E.C., Miller J.H. and Shiver, B.D.. 2004. The role of herbicides for enhancing forest productivity and conserving land for biodiversity in North America. Wildlife Society Bulletin. **32**: 1028-1041.

World Health Organization. 1994. International programme on chemical safety. Environmental health criteria 159—glyphosate. World Health Organization, Geneva, Switzerland.

Table 1. Summary of spray block and artificial exclusion zones sizes and nominal treatment rates for experimental sites receiving aerial applications of glyphosate (Vision) herbicide.

Year	**Block**	**Spray**	**Time**		**Application Rate**		**Block**	**Exclusion Zone**		
	#	**Date**	**Start**	**Finish**	**(L /ha)**	**(kg a.e./ha)**	**Size (ha)**	**Width (m)**	**Length (m)**	**Area (ha)**
2002	1	7-Aug	6:21	8:32	7	2.5	133.9	400	160	6.4
2002	5	8-Aug	6:36	8:02	7	2.5	110.8	200	200	4
2003	51	12-Aug	20:14	21:02	5.3	1.9	43.6	200	200	4
2003	55	12-Aug	8:48	10:19	5.3	1.9	71.6	300	250	7.5
2003	61	17-Aug	9:42	10:25	5.3	1.9	49.6	300	200	6
2003	62	17-Aug	7:44	9:21	5.3	1.9	91.1	250	200	5
2003	65	17-Aug	10:47	11:27	5.3	1.9	42.7	250	250	6.3
2003	66	1-Sep	10:06	11:49	5.3	1.9	94.1	300	300	9
AVG							**69.4**			**6**

Note: All blocks located on the Gordon Cosens forest, near Kapuskasing Ontario and treated via fixed-wing aircraft and piloted by P. Hodgins (Grumman Ag-Cat C-GQHQ; General Air Spray Ltd.). The aircraft was equipped with fully integrated AG-NAV2 and auto-booms calibrated to deliver volume application rates of 17 L/ha with a swath width of 20 m at a pressure of 158.6 kPa. Block size is for net area treated (i.e. total ha – exclusion zone ha). Spray blocks receiving applications of 7L/ha (2.5 kg a.e./ha) were made for the purpose of chemical site preparation while all others were for conifer release.

Table 2. Summary of Critical Application and Meteorological Parameters.

Block #	Release Height (m agl)	Flight Speed (km/hr)	Flight Path (Azimuth)	Track Error (m)	Wind Direction (Azimuth)	Wind (Class)	Wind Speed (km/hr)	Relative Humidity (%)	Air Temp. (oC) 13 m
1	28(1)	187(3)	22/211	0(2)	5 (0-22)	Axial	0.2 (3)	90 (82-97)	10 (7-12)
5	32(1)	170(3)	136/316	0(4)	31 (0-62)	Cross	1 (4)	90 (83-95)	10 (9-12)
51	27(1)	168 (3)	31/212	NA	222 (220-224)	Axial	5 (14)	44 (39-47)	22 (22-23)
55	26(2)	170(3)	132/312	1(3)	215 (212-219)	Cross	6 (12)	65 (52-74)	15 (12-17)
61	28(1)	170(3)	0/181	0(2)	135 (0-360)	Quarter	2 (7)	66 (59-72)	14 (13-15)
62	36(1)	170(3)	132/312	-1(6)	117 (0-360)	Axial	1 (8)	83 (67-91)	11 (8-13)
65	28(1)	169(3)	45/229	0(4)	156 (0-340)	Cross	5 (11)	60 (52-63)	16 (15-16)
66	35(1)	169(3)	0/180	0(2)	NA	NA	NA	NA	NA
AVG	**30**	**172**					**3**	**71**	**14**

All data values are means with bracketed values as measures of variation differing depending upon the measurement, for release height and air speed, these values are coefficients of variation, for track error the bracketed value is a standard deviation while for wind direction, relative humidity and temperature bracketed values are ranges.

Spray period, release height, air speed, flight line azimuths and track error estimates were derived from analysis of electronic guidance (AG-NAV2) file data during periods in which spray booms were on.

Wind direction, wind speed, relative humidity and air temperature were determined from CR10 meteorological monitoring stations located on or proximal to the spray block. Winds were classified as axial, quartering or cross-wind condition depending on the differential (0-30, 30-60, 60-120 degrees respectively) between mean wind direction and flight path azimuth.

Table 3. Summary of mean glyphosate deposition on target and beyond 30 m into the artificial exclusion zone.

	On-Target			Within Exclusion Zone *			
Block	**N**	**Mean****	**CV**	**N**	**Mean**	**CV**	**%*****
1	60	1256	42	30	271	115	22
5	70	1521	46	30	778	109	51
51	50	1512	47	29	645	43	43
55	47	1074	57	28	245	107	23
61	50	907	69	30	46	170	5
62	48	1141	43	29	125	126	11
65	38	623	69	22	73	263	12
Avg	**52**	**1148**	**53**	**28**	**312**	**133**	**24**

* for observations beyond 30 m from any exclusion zone boundary

** mean total ug glyphosate per 98 cm2 collector

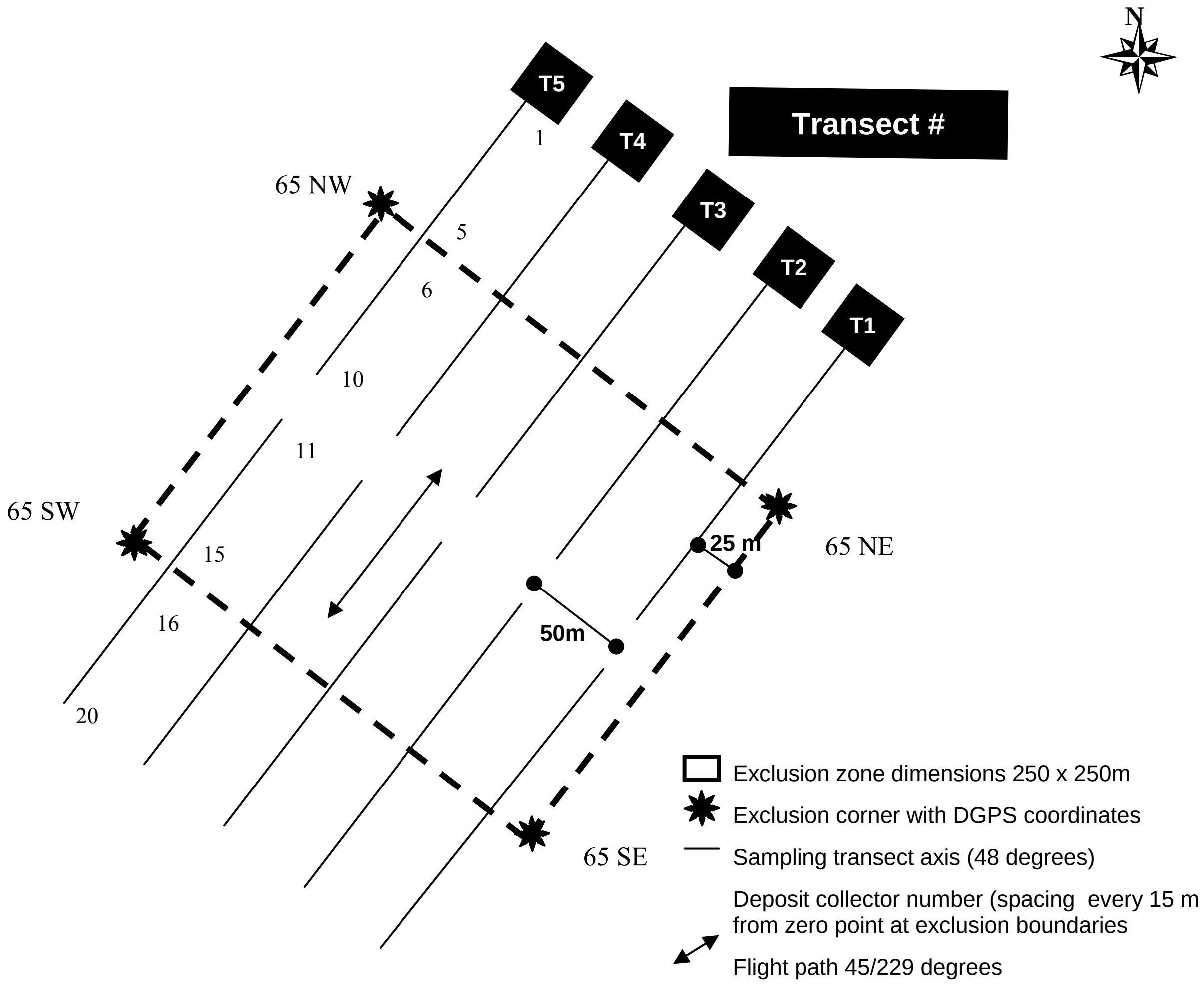
*** mean deposition within exclusion zone expressed as % of mean on-target deposition

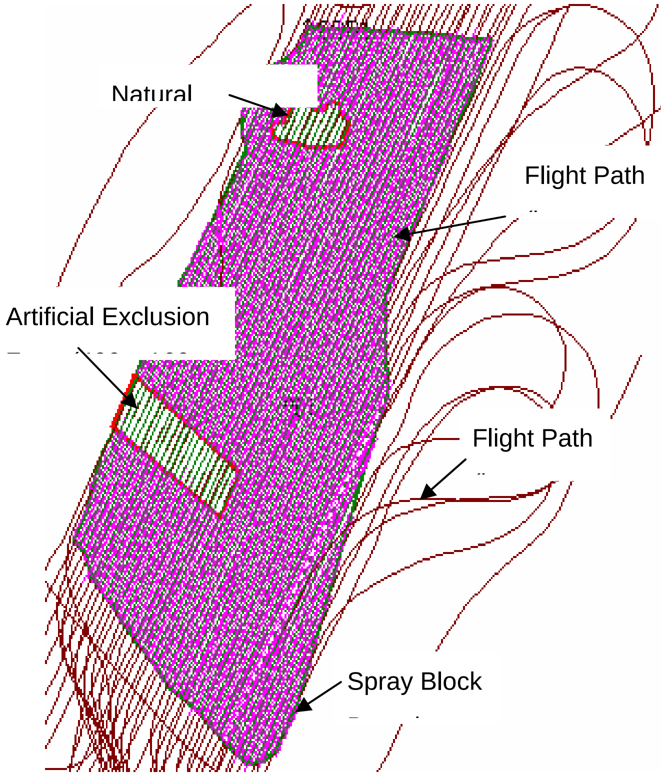
Table 4. Estimated area of live vegetation within artificial exclusion zones and derivative estimates of actual silvicultural exclusions realized in seven experimental spray blocks.

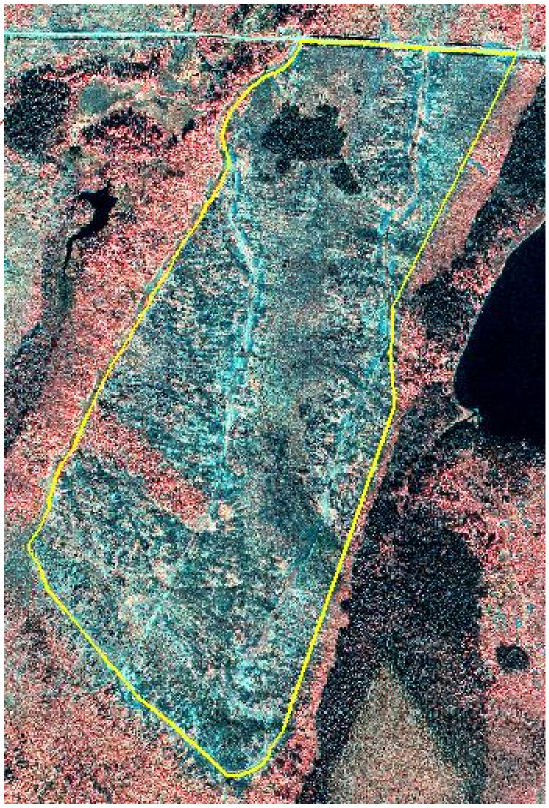
Spray Block #	Artificial Exclusion (ha)	Area of Live Vegetation Within Boundaries			Silvicultural Exclusion Area as % of Artificial Exclusion		
		Satellite	**Digital**	**DGPS**	**Satellite**	**Digital**	**DGPS**
1	6.4	5.3	NA	NA	83	NA	NA
51	4	0.7	NA	NA	18	NA	NA
55	7.5	5	5.2	4.9	67	69	65
61	6	4.4	4.5	4.9	73	75	82
62	5	3.5	4	4	70	80	80
65	6.3	5	5.4	5.4	79	86	86
66	9	6.3	6.9	7.4	70	77	82
Mean	**6**	**4**	**5**	**5**	**66**	**77**	**79**

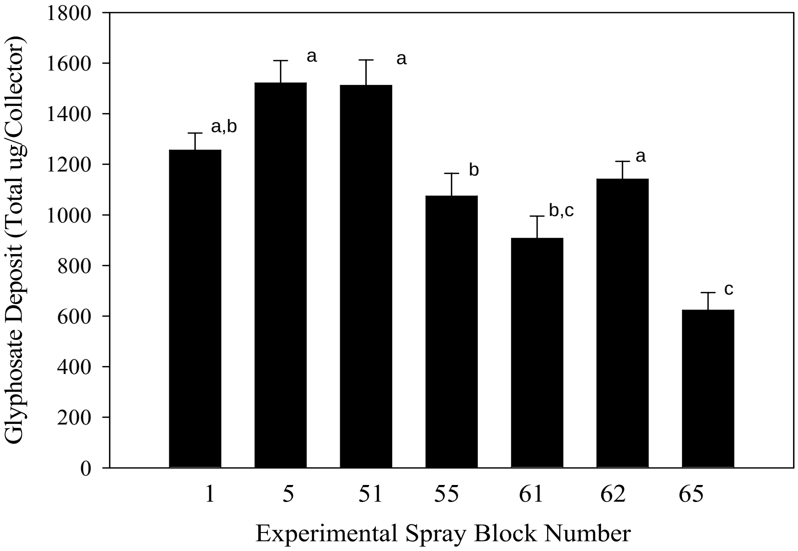
Figure Captions

1. Representative experimental design schematic (Block 65) showing relative layout of the artificial exclusion zone, chemical deposition sampling transects and flight paths
2. Representative graphic output file from the electronic guidance system (AG-NAV2) (2a) and corresponding near-infrared satellite image (2b).
3. Comparative Mean (± SE) deposition within the target area of experimental spray blocks.
4. Comparative patterns of glyphosate deposition on experimental spray blocks 1 (4a) and 51 (4b).
5. Comparative exponential decline models of mean glyphosate deposits relative to downwind distance from exclusion zone boundaries in experimental spray blocks 1 and 51.
6. Phytotoxicity contours as estimated by three different methods for block 65 shown as overlays on true-colour digital (6a) and near-infrared satellite (6b) images for comparison.
7. Mean phytotoxic incursion distances relative to upwind exclusion zone boundaries.


N
Transect #
T5
T4
T3
T2
T1
1
5
6
10
11
15
16
20
65 NW
65 SW
65 NE
65 SE
25 m
50m
Exclusion zone dimensions 250 x 250m
Exclusion corner with DGPS coordinates
Sampling transect axis (48 degrees)
Deposit collector number (spacing every 15 m from zero point at exclusion boundaries
Flight path 45/229 degrees


Natural
Flight Path
Artificial Exclusion
Flight Path
Spray Block





All data normalized to nominal rates of 1.9 kg a.e./ha glyphosate and collector size of 98 cm^2.
On-target deposits followed by different letters are statistically different ($p = 0.05$) as determined by Kruskal-Wallis ANOVA on ranks and Dunn's multiple comparison procedures.

Fig. 4a. Pattern of Glyphosate Deposition on Block 1

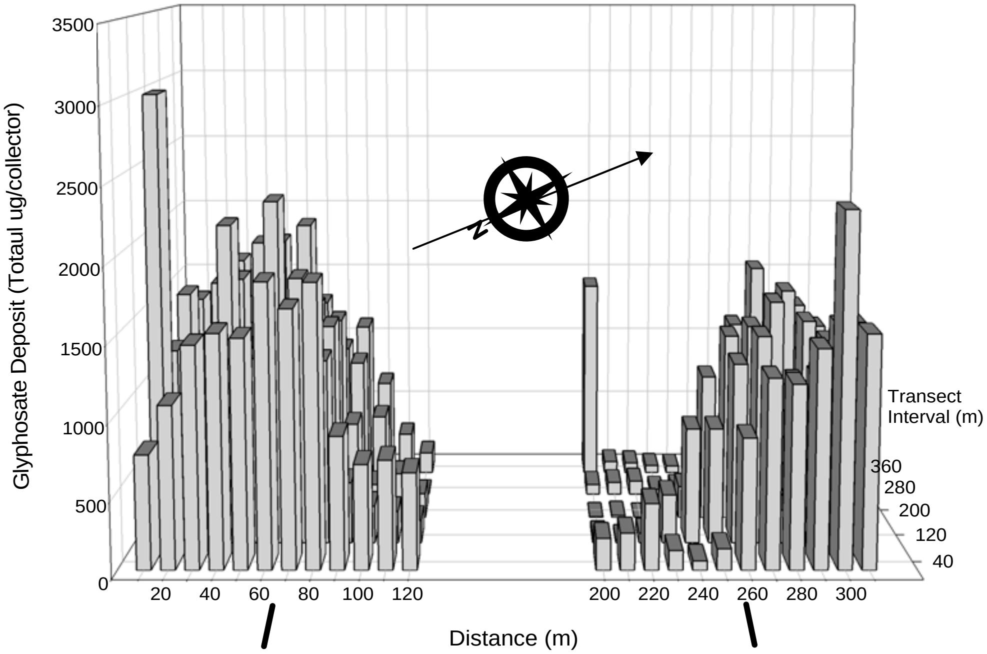
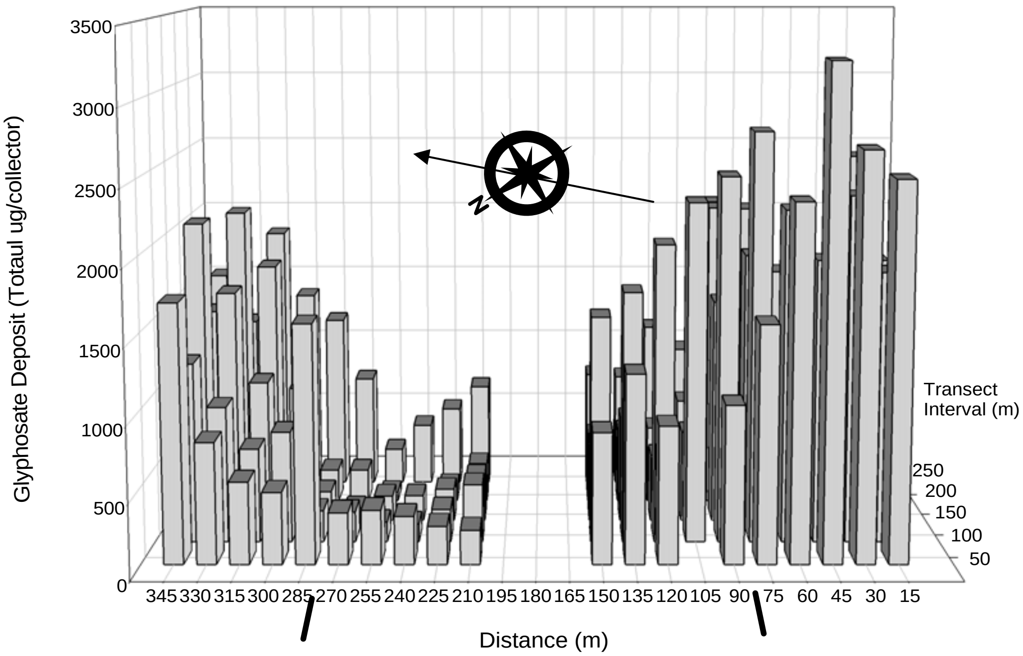
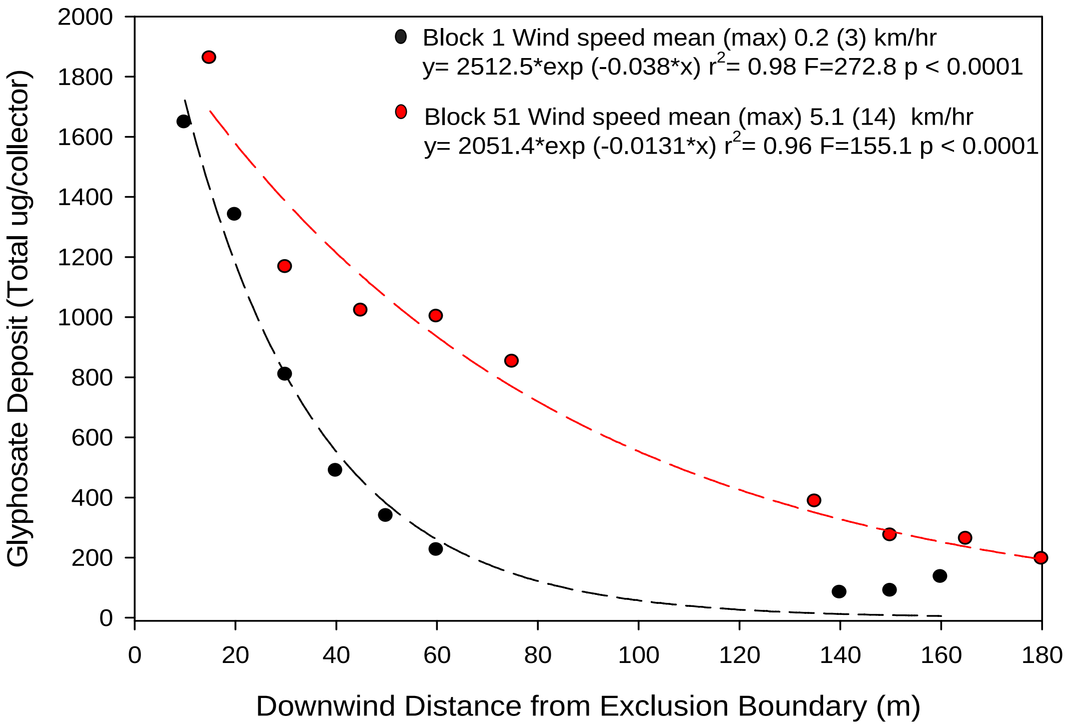


Fig. 4b. Pattern of Glyphosate Deposition on Block 51



Artificial exclusion zone

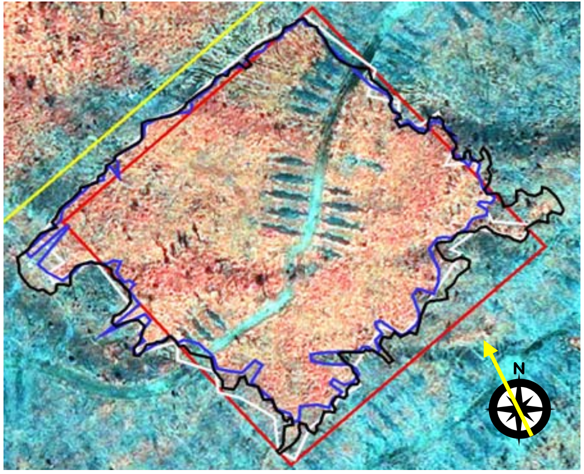
Compass rose shows general orientation and arrow indicates mean wind direction.



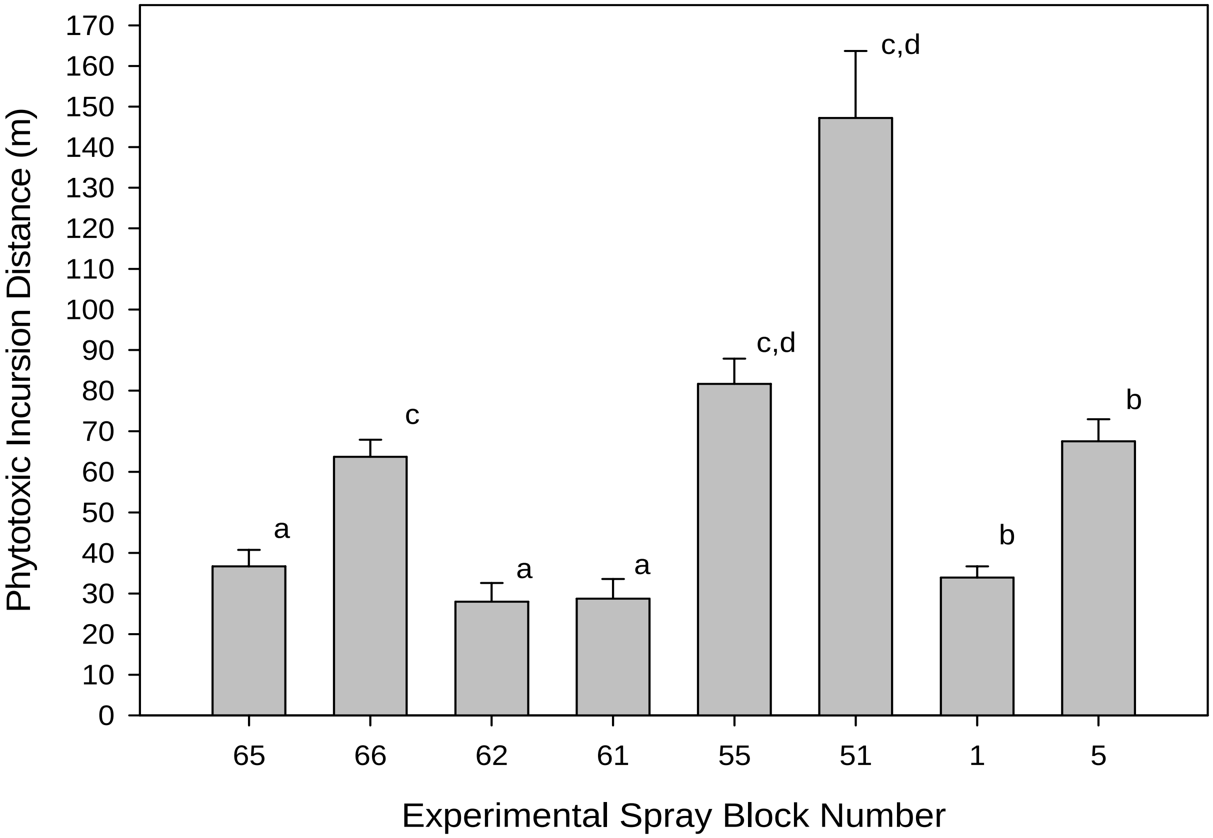
Note: One anomolous data point at 60 m distance was ommitted from the regression analysis for block 1.

Fig. 6a.

Fig. 6b.



True colour digital (a) and near-infrared satellite (b) image close-ups of the area about the artificial exclusion zone (250 x 250 m red square) imposed on spray block 65. The yellow arrow shows approximate mean wind direction (156 degrees). In the digital image live vegetation appears green whereas herbicide-killed vegetation appears as mottled grey/brown. In the satellite image, live vegetation appears as mottled-pink with herbicide killed vegetation as mottled aqua-marine. The blue line shows the phytotoxicity contour line as defined using digital image analysis and the green line defines the phytotoxicity contour as determined by satellite image analysis. The contour determined by ground-based DGPS tracking (omitted for clarity), is essentially identical to the digital image analysis contour. A small skidder trail bisects the exclusion zone and several slash piles, aligned on either side of the trail are clearly visible in both images.



Mean incursion distances estimated based on multiple digital measurements between phytotoxicity contours and upwind artificial exclusion boundaries in each experimental spray block. Phytotoxicity contours delineated as the boundary between live and dead vegetation based on near-infrared satellite imagery. Estimates annotated by different letters are signficantly different (p=0.05) based on Kruskal-Wallis ANOVA and Dunn's multiple comparison procedures.