Performance of an air-assist forestry boom sprayer

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Darvishvand, M. and Brown, R.B. 1997. **Performance of an air-assist forestry boom sprayer**. Can. Agric. Eng. 39:281-287.

Air-assist, where a stream of high-velocity air is directed over or close to the spray emitted from a nozzle, is used to improve deposition efficiency and to reduce spray drift with agricultural sprayers. Forestry industries are concerned with the same issues. This study was initiated to investigate air-assist as a means of improving spray penetration and deposition from a boom sprayer while reducing drift potential in a canopy of wild red raspberry plants (*Rubus idaeus* L.), a weed common in Ontario forest regeneration sites. A small air-assist boom sprayer was built and two sets of experiments were conducted, one in a walk-in wind tunnel and the other at a field site. Two air-assist configurations were used: direct-assist and air-curtain. Results showed that both configurations increased spray penetration, providing improved spray deposition on targets located within the canopy. Air-assist also reduced the potential for drift under windy conditions. However, the air-curtain configuration was not effective in a crosswind situation. **Keywords**: spray, air-assist, drift, penetration, forestry.

L'assistance par air est un procédé dans lequel un courant d'air à grande vitesse est dirigé sur ou près d'une pulvérisation émise à partir d'une buse. Le procédé d'assistance par air est utilisé dans les pulvérisateurs agricoles pour augmenter l'efficacité de la déposition et réduire la dérive de la pulvérisation. Les industries forestières s'intéressent aussi à ces questions. Cette recherche a donc pour but d'étudier le procédé d'assistance par air comme moyen d'améliorer la pénétration et la déposition d'une pulvérisation émise par un pulvérisateur à rampe. L'étude a été menée sur un couvert forestier de framboises rouges sauvages (*Rubus idaeus* L.), une mauvaise herbe commune dans les sites de renouvellement de la forêt ontarienne. Un pulvérisateur à assistance par air de petite taille a été construit et deux expériences ont été menées: une dans un tunnel aérodynamique de plain-pied et l'autre sur le terrain. Deux configurations d'assistance par air ont été utilisées: assistance directe et rideau d'air. Les résultats ont montré que les deux configurations augmentaient la pénétration de la pulvérisation, donnant une meilleure déposition de la pulvérisation sur des cibles placées dans le couvert forestier. De plus, dans un environnement venteux, l'assistance par air a réduit la dérive de la pulvérisation. En revanche, la configuration rideau d'air n'a pas été efficace en présence de vent latéral. **Mots clefs**: pulvérisation, assistance par air, dérive, pénétration, foresterie.

INTRODUCTION

Demand for wood and wood products continues to increase as forest reserves dwindle, so forest management technology is an important issue world wide. In Canada, coniferous forests are commercially important because softwood is superior for building material and paper and conifers regenerate quickly under our climate. Early pine seedling growth is impressive when competing weeds are controlled, with 3-year old trees as much as three times the size of trees growing in competition with herbaceous weeds (Mitchell and Lowery 1988). Forest management technology to control unwanted vegetation has been the focus of much research recently, mainly directed at refining herbicide chemistry and application (Wagner 1993). Chemical control of vegetation is popular with forest managers because it requires less labor than mechanical methods and is efficient and economical (Lund-Hoie 1985). However, despite its contribution to forest productivity, herbicide use has come under increased public criticism because most people believe that herbicides are harmful to wildlife and humans living in or near the forests, contrary to the preponderance of scientific evidence (Wagner 1993).

The usual silvicultural harvest practice in Canada has been clearcutting, where all trees in an area are harvested and the site is then replanted as soon as possible. With clearcutting there are risks of excessive soil erosion or invasion by brushy species before a tree stand can be established. However, the large open areas are also well suited to aerial spraying or mechanical brush control. Recently there has been a move to the shelterwood harvest system, where enough mature trees are left on a site to provide cover conditions and the residual trees are the seed source for regeneration. Brush invasion and soil erosion are reduced because of the presence of the sheltering trees which can be harvested once the new stand is established. A disadvantage of this system is that aerial herbicide application is hindered by the sheltering trees. The strip shelterwood system involves cutting regular swaths through the forest for access, leaving treed strips that are twice as wide as the height of the crop trees. This system is easier to manage and is more accessible for spraying. There is an interest in developing ground sprayers and mechanical site preparation equipment that can negotiate under and around the residual trees in either system.

Controlling spray drift and reducing chemical application rates for ground spraying are current goals in agricultural engineering research. Sprayer technology developed in agriculture may also be applicable to forestry. For example air-assist, where a stream of high velocity air is directed over or close to the spray emitted from a nozzle, has been adopted in agricultural spraying. Droplet trajectory from these sprayers is controlled by directing the air flow into the plant canopy. Air-assist has received a lot of attention due to claims of drift reduction or improved canopy penetration

(Taylor et al. 1989; Bode 1988; Quanquin et al. 1989). Watson et al. (1984) demonstrated improved canopy penetration and coverage with air-assist spraying in corn and soybean fields.

There are significant differences between ground-based spraying in forestry and agriculture. In forestry, the plant and weed canopies are more heterogeneous and are much higher at the time of spraying, usually reaching a height of more than 1 metre. Forestry ground-based spraying equipment must be much narrower and more maneuverable than a field sprayer and much more rugged due to the rough terrain. However, the same issues that are driving agricultural sprayer research, namely deposition efficiency and off-target drift, are concerns in forestry.

OBJECTIVES

The objective of this study was to evaluate the performance of an air-assist sprayer as a means of controlling off-target deposition (near-field spray drift) while improving penetration and deposition of spray within a canopy of wild red raspberry plants (*Rubus idaeus* L.), a common weed in Ontario forest regeneration sites. Two air-assist configurations were used. In the direct-assist configuration, the air stream was channeled vertically downwards over the nozzles to entrain the spray. The air-curtain configuration directed air at an angle of 30° ahead of the nozzles to create a protective curtain or shield for the spray. Tests were conducted with the sprayer to:

1) evaluate the interaction between air flow configuration and wind angle on the amount of on-target spray deposition in a wind tunnel, and
2) determine the effects of air-assist on spray penetration and deposition for a canopy of wild red raspberry plants in the field.

MATERIALS AND METHODS

A small air-assist boom sprayer was built for the experiments (Fig. 1). It was designed to fit into the wind tunnel and to be attached to a tractor-mounted front-end loader for field trials. The 1.5-m boom had four 80-degree flat fan nozzles each delivering 0.64 L/min at a pressure of 210 kPa (LFR 80-2R, Delavan Agricultural Products Operation, Lexington, TN) mounted on 0.5-m centers. The sprayer was equipped with a centrifugal fan (Model GPI-610, Daltec Industries Ltd., Guelph, ON) powered by a 4.1-kW gasoline engine (Honda Model GX160). A tubular air bag system 0.4 m in diameter made of fibre-reinforced PVC was used to distribute air over the full length of the boom. Disks of plywood were used for the ends of the air bag and a continuous discharge slot ran the length of the bottom side. The slot was fitted with full length adjustable flaps on hinges to change the outlet opening width and the direction of air deflection (Fig. 2). With the outlet slot opening set to 10 mm and the engine at full throttle, the average velocity 50 mm below the slot was 7 m/s, with a range of 6-8 m/s over the length of the duct. Airflow measurements were made with a 150-mm diameter vane anemometer (Model DVA 6000T, Air Flow Developments Canada Ltd., Mississauga, ON).

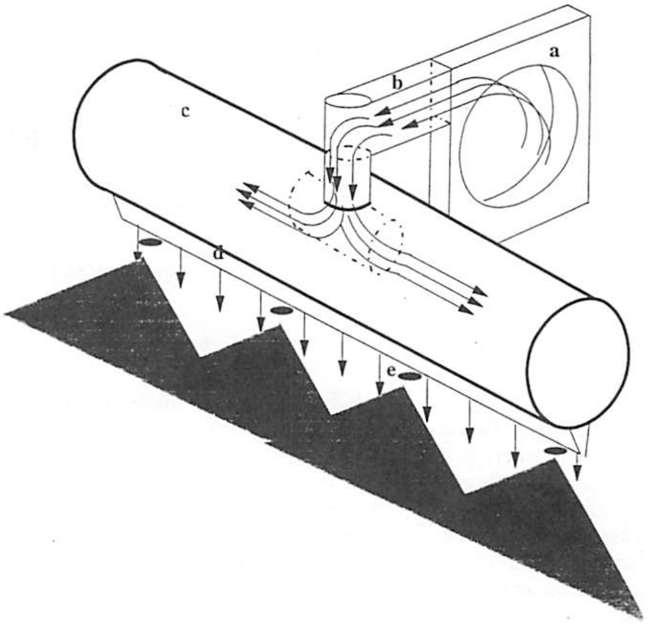


Fig. 1. The distribution system for assist air flow (a. centrifugal fan, b. transition duct and dual outlet, c. flexible air duct, d. air slot, e. nozzle).

Wind tunnel experiments

The wind tunnel was 2.2 m wide and 1.5 m high with a working length of 8.5 m. There is no general agreement in the literature on a safe maximum wind speed at or below which ground spraying would always be advisable. The wind tunnel

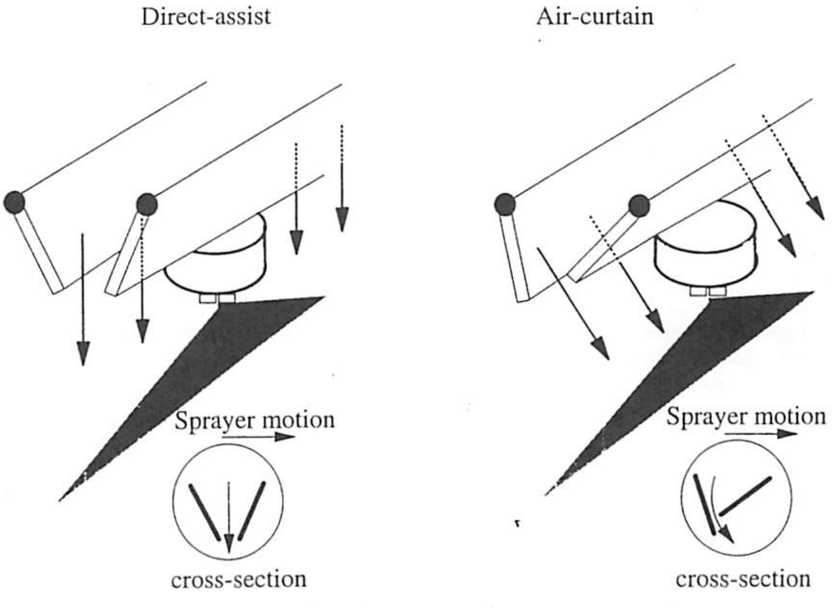


Fig. 2. Comparison between direct-assist and air-curtain configurations.

air speed was set to 4.2 m/s because most field sprayer operators would be concerned about poor deposition and excessive drift with a sustained wind of that speed.

The two air-assist configurations were evaluated to test the effectiveness of each for keeping spray deposits within the boom swath with different wind directions relative to the orientation of the sprayer. Wind directions were chosen to simulate a head wind (wind velocity 180° relative to the line of sprayer travel), a cross wind (90°), and a leading wind (135°). Three replications of each combination were conducted and the order of experiments was randomly chosen. A third set of trials was conducted without air (no-assist) and a control was run in which there was neither wind nor air-assist. While on-target deposition is inversely related to drift losses, it does not differentiate between losses due to evaporation and drift. Nevertheless, if on-target recovery is maximized for a particular set of conditions, drift will be minimized. In the wind tunnel, on-target spray deposition was defined as the amount of spray collected by a 2-dimensional patternator 1.05 m wide and 0.9 m long located mid-way between the ends of the boom. The patternator comprised a matrix of 42 cells, each one an acrylic plastic box 150 mm square with beveled top edges flush with the floor of the wind tunnel. The sprayer boom was positioned so that the second of six rows of patternator boxes was directly beneath the nozzle center line (i.e., one row was upwind of the spray fan - see Fig. 3). Boom height was 0.5 m from the top edge of the boxes with the nozzles pointing vertically downwards.

The tare mass of each dry box was recorded before every 2-minute spraying experiment and the cells were immediately re-weighed afterward. Relative spray recovery as a percentage was calculated using the no-wind, no-assist combination in each replication as a reference. Air temperature, relative humidity, and wind speed were measured for each experiment. Air conditions in the building housing the wind tunnel were maintained at 21°C and 30-40% RH.

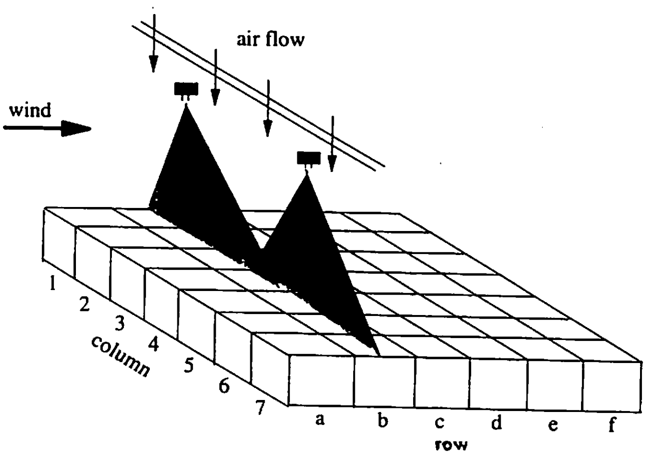


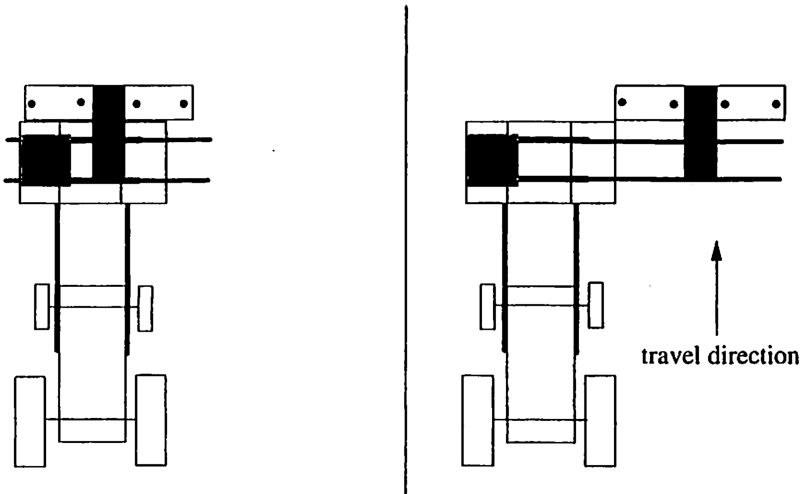
Fig. 3. The patternator used to gather on-target spray recovery data in the wind tunnel.

Field trials

Field trials were run to measure the amount of spray deposition within a plant canopy for no-assist, direct-assist, and air-curtain conditions. The experiments were conducted near Guelph, ON in an abandoned field which was reverting to a natural state of mixed hardwood forest. Wild red raspberry was the major competitor for the trees and brush. The height of raspberry canes was between 1 m and 1.5 m and the density of leaves was quite variable. Raspberry canes from previous years had fewer leaves than new growth. Two large patches of canes, each about 10 m in length and 3-4 m wide, were selected for the test site. The two patches were roughly perpendicular to each other, allowing trials to be done at different wind angles. Since the spraying was done in the field, air temperature, relative humidity and wind speed were not controlled. However, the trials were conducted within two wind speed ranges: low wind (1-2 m/s) and high wind (2-4 m/s). Field trials were conducted on 6 different days: 3 each for high and low wind conditions. The range of air temperatures observed over the trials was 22 to 27°C and humidity was between 47 and 75% RH.

The sprayer was attached to a tractor-mounted front-end loader because it had to operate about 0.5 m above the top of the raspberry canopy. The bucket of the loader was removed and an adjustable sub-frame was added in order to offset the position of the sprayer (Fig. 4). This was necessary so that the sprayer swath was not crushed by the tractor wheels and frame. The height of the spray boom above the canopy was adjusted by raising the loader arms.

Because the amount of spray penetration and deposition



a) transportation position of sprayer

b) spraying position of sprayer (off-set)

Fig. 4. Mounting system for the air-assist sprayer as used in the field trials.

within the canopy was of interest in field experiments, deposits were collected on Kromekote® card targets (Job-Redi®, Business Communication Papers, Intercity Papers Ltd, Mississauga, ON). Rhodamine powder dye (Rhodamine WT acid red # 388, A. S. Patterson, Willowdale, ON) was added to the sprayer water tank at a concentration of 0.2%. This was the same concentration used by Brown et al. (1994) who determined the spread factor for droplets on Kromekote® cards. That spread factor was also used here to estimate the original diameter of droplets deposited. Three targets were attached to each of 10 raspberry canes in the patch at three different levels within the canopy: top, 2/3 height, and 1/3 height.

Mature compound leaves of red raspberry consist of three leaflets with a total area of approximately 2500 mm^2. Triangular target cards (70 x 70 x 100 mm) with similar shape and area were created. The canopy in both patches was between 1.1 m and 1.5 m tall, so 1.3 m was chosen as an average height and the targets were installed on the raspberry canes at levels of 1.3 m, 0.86 m, and 0.43 m from the ground. Compound leaves were removed from canes and replaced with small alligator clips on pieces of copper wire about the same length as the leaf stems. Target cards were then clipped in place at the same orientation as the original leaves which were removed. At the end of each experiment the sprayed cards were allowed to dry and then were removed, sealed in individual plastic sample bags, and taken to the lab for analysis. Care was taken in placing and removing the card targets so that the canopy was disturbed as little as possible.

RESULTS

Wind tunnel experiments

Three replications of the treatments plus the controls, for a total of 30 trials, were conducted in the wind tunnel. The percentage of water recovery from the patternator with no air assist and no wind was used as the reference (i.e., 100% recovery). A two-way analysis of variance was done on the experiment to find the significance of air-assist configuration and wind angle factors and their interaction. The air-assist configuration and wind angle were both highly significant factors ($P \leq 0.01$) with respect to the amount of on-target deposition. The interaction of configuration and wind angle was also significant at the same probability level.

In Fig. 5, the average spray recovery volume for three replications of treatments with respect to the three wind angles is shown. Spray recovery volume was calculated relative to the control (no-assist, no-wind treatment) within each replication. The differences between each air-assist configuration and the corresponding no-assist treatment were also applied in the Least Significant Difference Test (Kuehl 1994) to determine if direct-assist losses were statistically different from air-curtain losses. At the 180° wind angle, the air-curtain configuration reduced off-target losses by 69%; this was significantly better ($P \leq 0.05$) than the 51% reduction for direct-assist. Also, at the 135° wind angle the air-curtain configuration reduced losses more than direct-assist (66% vs 54%). However, at the 90° wind angle the air-curtain configuration caused a significant increase ($P \leq 0.05$) in off-target losses of 57% while direct-assist showed a reduction of 85%.

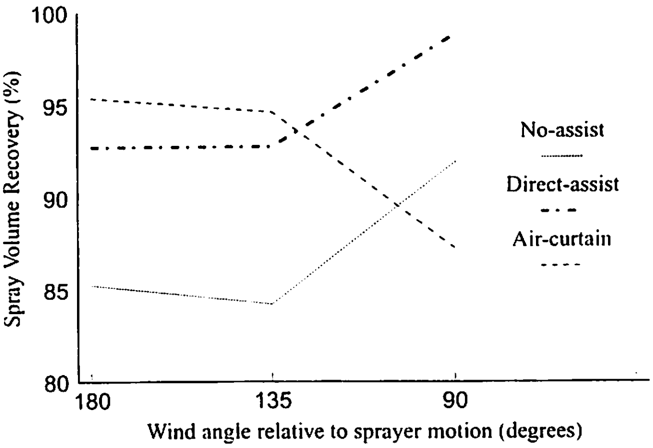


Fig. 5. The effect of wind angle and air-assist configuration on spray recovery within the target area.

Field experiments

The size and the number of dye stains on the target cards were determined by counting them under 20x magnification with an optical comparator (Model PJ-250B, Mitutoyo Co. Ltd., Tokyo, Japan). Because of the large number of droplet traces on each card, data were collected from three randomly placed fields on each card. Also, instead of recording the size of droplet traces individually, they were classified into 9 size classes: 50-100, 100-150, 150-200, 200-250, 250-300, 300-400, 400-500, 500-700, and 700-1000 µm. The number of droplet traces per class for data analysis was found by averaging the total number of droplet traces found on target cards located at the same levels. Dye-stain size on the Kromekote® card targets is not the actual diameter of the spray droplet in flight because the droplet spreads after deposition. The volume of spray deposited on the cards was calculated with the spread factor calibration equation determined by Brown et al. (1994) for monodisperse droplets of water and Rhodamine dye in the range of 30 to 220 µm in diameter:

$$D_{sphere} = 12.8 + (0.461 \times D_{stain}) \tag{1}$$

where: D_{sphere}, D_{stain} = diameters (µm). Equation 1 is probably only valid for the particular batch of Kromekote® cards that was used by Brown et al. (1994) and which was also used in these experiments. Since the droplets were counted within 9 different size class ranges, the midpoint of each range was used to calculate the class droplet diameters from Equation 1. Spray volume calculations were made on the basis of the class diameter. The results of the field experiments are shown in Fig. 6.

The significance of air-assist configuration on the amount of spray penetration and deposition in the raspberry canopy was evaluated. At canopy levels 1 and 2 (top of the canopy and 2/3 canopy height) neither air flow configuration was found to be significant relative to no-assist ($P \leq 0.05$). However, at the lowest level (1/3 canopy height) the air-curtain configuration significantly increased total spray deposition compared to the no-assist situation ($P \leq 0.05$). The direct-as-

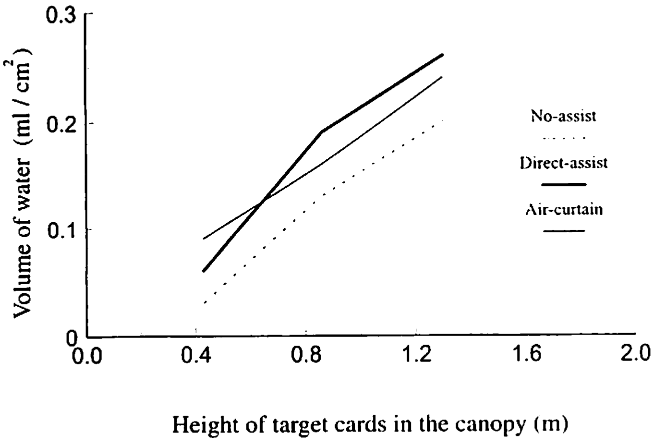
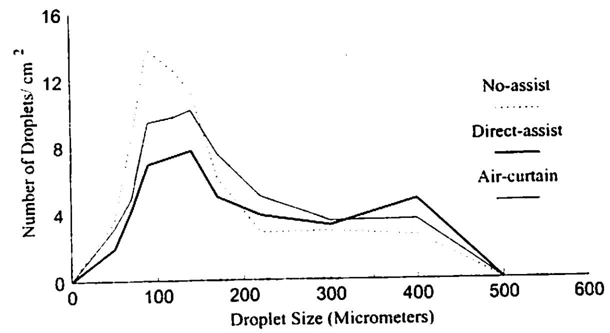
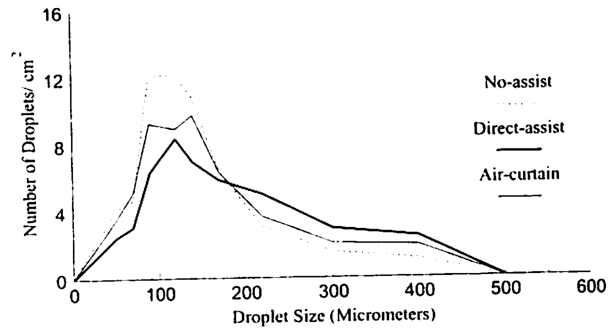


Fig. 6. Total volume of spray deposited on card targets inside the wild red raspberry canopy.

a. Droplet Spectrum on Level One



b. Droplet Spectrum on Level Two



c. Droplet Spectrum on Level Three

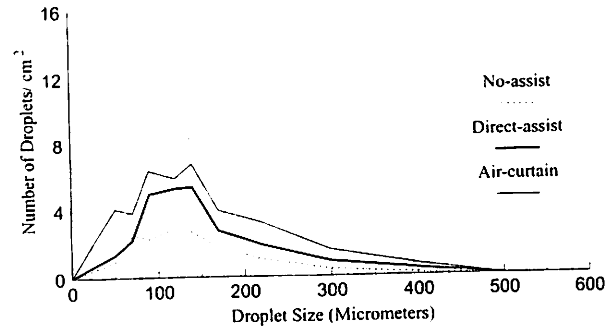


Fig. 7. Size spectra of spray droplets deposited on card targets at three levels inside the wild red raspberry canopy.

sist configuration moderately affected spray deposition (i.e., it was not significantly lower than that of the air-curtain, nor higher than the no-assist application).

The performance of each treatment was also evaluated by comparing the droplet spectra on each level as shown in Fig. 7. The trends on levels 1 and 2 were the same. The number of droplets within the range of 0-200 µm for no-assist was higher than that of the two other conditions, but more droplets within the range of 200-500 µm were deposited with the direct-assist and air-curtain configurations than with the no-assist applications. On level 3, direct-assist and air-curtain applications deposited more droplets in almost all size classes than the no-assist situation.

DISCUSSION

Wind tunnel experiments

The objective of the wind tunnel experiments was to evaluate the air-assist configurations with respect to on-target deposition. This was determined as the percent recovery of water volume collected in the patternator target cells relative to the total volume sprayed during a 2-minute trial.

The results indicated that both air flow configuration (direct-assist or air-curtain) and wind angle, as well as their interaction, significantly affected the potential for spray drift. For constant wind velocity at wind angles of 180° (headwind) and 135° (leading wind), the air-curtain setup was more effective. While the direct-assist configuration was also significantly better than the no-assist condition at those wind angles, its performance was not as good as the air-curtain.

With a crosswind (i.e., a 90° wind angle), the efficacy of the air-curtain configuration changed dramatically. It did not improve spray deposition and actually increased the potential for spray drift compared to the no-assist condition. Direct-assist was very effective at the 90° wind angle, however, and 98% spray volume recovery was achieved relative to the control. The direct-assist configuration was designed to entrain spray droplets, introducing a significant vertical component to each droplet trajectory. That vertical component would cause direct-assist droplets to reach the target sooner than unassisted spray droplets and would happen regardless of the direction of the wind. On the other hand, the effect of the air-curtain configuration was to shield the spray pattern from the wind in much the same way that a shroud would. The interaction of the forward-directed air-curtain stream with a headwind opposing it can be visualized as vector addition and the magnitude of the horizontal component of the resultant (i.e., the effective horizontal wind acting on spray droplets) would be smaller. However, in a crosswind (or a tailwind) situation the air-curtain assist would not reduce the horizontal component of wind and could even increase it.

At the wind speed of 4.2 m/s in this study, the amount of on-target deposition was increased significantly by using either air-assist setup. However, caution must be exercised with the air-curtain configuration because its efficacy depends upon wind angle. At wind angles of 180° and 135° (or within 45° of a direct headwind situation) its performance in reducing spray drift was better than air-assist. But because spray droplets are not entrained, the air-curtain configuration is apparently effective only for a headwind situation.

Field experiments

In the field experiments, the objective was to evaluate spray penetration and deposition inside the canopy. This is important for two reasons. Although herbicides used in forestry are mostly systemic and they affect the whole plant after being applied to its leaves, spray may be intercepted by overtopping layers in the canopy. Most canopies of undesirable trees and brush comprise several different species with different heights and in order to remove all species the herbicide droplets have to gain enough momentum to reach the lower levels of those canopies. Also, in a stand of red raspberry canes, the upper canopy of old canes might not have enough leaves to be affected by herbicides and in that case the spray droplets would have to penetrate to the lower canopy to be effective.

It is apparent from the droplet spectra data (Fig. 7) that the pattern of deposition for spray droplets ranging in size from about 250 to 500 μm was similar at all three levels. Generally the number of droplets deposited was lowest for the no-assist situation, with a slight improvement for either air-assist configuration. The smaller droplets (0-200 μm) behaved quite differently. The no-assist application on the two upper levels produced the highest numbers of droplets deposited in this range. However, at level 3 of the canopy, the no-assist application had the lowest number of droplets deposited. The air-curtain configuration produced the highest number. In the field it was obvious that the air flow bent the raspberry canes forward in the direction of sprayer travel. Apparently droplets within the 0-200 μm range followed the path created by the air flow in either configuration and were carried through the canopy to deposit at lower levels.

Analysis of variance for the field experiment data (Completely Randomized Model) showed that on level 1 (the top of the canopy) there were no significant differences among no-assist, direct-assist, and air-curtain sprayer configurations with respect to the amount of spray deposition for a single trial ($P = 0.05$). There were significant differences among the repetitions since each trial was done on a different day and the meteorological conditions varied. On level 2, 0.43 m below the top of the canopy, the sprayer configurations had no significant effect on spray deposition at the 95% confidence level even with repetitions. The effects of meteorological variables on the volume of spray deposited was obviously less than on level 1. However on level 3, or 0.86 m into the canopy, there was a significant difference between no-assist and air-curtain spraying according to the protected LSD test. Trial-to-trial variation was found to be insignificant at that canopy level, so there was no effect of variable meteorological conditions.

The air-curtain configuration was more effective than direct-assist in maintaining on-target deposition and increasing spray penetration into the canopy as long as the wind direction was within 45° of a headwind (i.e., from 135 to 225° relative to sprayer travel direction). If the direction of travel must change constantly relative to wind direction, as it might when following swaths cut through a shelterwood forest management tract, then direct-assist would be preferred.

Significant improvements were found in on-target deposition and canopy penetration with an air-assist velocity of 7 m/s and an outlet slot opening 10 mm wide. The velocity of air flow was far less than that claimed by some commercial air-assist sprayers. For example, according to Quanquin et al. (1989) the Hardi Twin Sprayer (Hardi International A/S, Taastrup, Denmark) can generate air flow with up to 30 m/s discharge velocity. However, Womac et al. (1992) reported that for the same sprayer model the maximum air velocity measured 100 mm below the outlet slot was only 16 m/s. Of course the air speed, outlet slot opening, and volume of air delivery are all inter-related variables, so the effectiveness of an air-assist sprayer is dependent on its design and proper setup. The power required to supply air to the sprayer will limit the air-assist volume and velocity. Our prototype used about 2.5 kW per metre of boom length. A reasonable boom size for a forestry ground sprayer would be about 6 metres, and this would impose an estimated power requirement of about 15 kW. While higher air velocity may improve spray deposition or canopy penetration, the additional power requirement would be prohibitive.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions on the performance of an air-assist boom sprayer were drawn from this study:

1. The direct-assist configuration with an outlet velocity of 7 m/s was effective in reducing potential spray drift from flat fan hydraulic nozzles with a wind speed of 4.2 m/s and a wind direction varying from 90 to 180° relative to the direction of sprayer travel.
2. The total volume of spray deposit on card targets located at 3 levels within a canopy of wild red raspberry plants increased when air-assist was used with a hydraulic nozzle boom sprayer.
3. Direct-assist improved the penetration of spray into a canopy of wild red raspberry plants resulting in increased deposition of small droplets at lower levels.
4. Performance of the air-curtain setup was highly dependant on wind angle and for a cross wind the amount of on-target deposition was even lower than that of the no-assist condition. Direct-assist consistently improved on-target deposition at all wind angles investigated.
5. Direct-assist is generally more suitable for application of herbicides in shelterwood forest management because the sprayer path and therefore the effective wind angle changes frequently.

In view of the results of this study, it is highly recommended that future work be undertaken. Similar experiments for different types of nozzles should be conducted. Since in this study, only 80^0 flat fan nozzles were used, the effect of combinations of air-assist and other types such as hollow cone and flood jet nozzles is unknown.

The relationship between the amount of air-assist and the degree of wind protection should be investigated. In this study, a high pressure, low volume centrifugal blower was used to generate the air flow. Although the results of our experiments have shown that a 7 m/s discharge velocity for air flow significantly reduced drift potential, higher air-assist flow rates should be examined to determine if they would be beneficial.

REFERENCES

Bode, L.E. 1988. Air-assist, air-foil, and air-curtain sprayers. *Weed Technology* (2): 88-93.

Brown, R.B., M.M. Sidahmed and A. Sundarum. 1994. Droplet trajectories and deposition with an airblast forestry sprayer. *Journal of Environmental Science and Health* B29(4):831-853.

Kuehl, R.O. 1994. *Statistical Principles of Research Design and Analysis*. Belmont, CA: Wadsworth, Inc.

Lund-Hoie, K. 1985. Efficacy of glyphosate in forest plantation. In *The Herbicide Glyphosate*, eds. E. Grossbard and D. Atkinson, 328-338. London, England: Butterworth & Co.

Mitchell, R.J and R. F. Lowery. 1988. Herbaceous weed control in young pine plantation. In *A Manual on Ground Applications of Forestry Herbicides*, ed. J.H. Miller and R.J. Mitchell, 4.1-4.8. USDA Forest Service, Southern Region, 1720 Peachtree Road, NW, Atlanta, GA.

Quanquin, B.J., G.W. Anderson, W.A. Taylor and P.G. Andersen. 1989. Spray drift reduction and on-target deposition using the Hardi Twin system air assisted boom sprayer. ASAE Paper No. 89-1523. St. Joseph, MI: ASAE.

Taylor, W.A., P.G. Andersen and S. Cooper. 1989. The use of air assistance in a field crop sprayer to reduce drift and modify drop trajectories. In *Brighton Crop Protection Conference -Weeds*, 631-639. Farnham, Surrey, England: British Crop Protection Council.

Wagner, R.G. 1993. Research direction to advance forest management in North America. *Canadian Journal of Forestry Research* (23): 2317-2327.

Watson, D.B., R.L. Wolf and G. Kapusta. 1984. Development of improved row crop spraying. ASAE Paper No. 84-1007. St. Joseph, MI: ASAE.

Womac, A.R., J.E. Mulroony and W.P. Scott. 1992. Characteristics of air-assisted and drop-nozzle sprays in cotton. *Transactions of the ASAE* 35(5): 1369-1375.