PAPER NO. 87-1041

HERBICIDE INCORPORATION ANALYSIS USING COMPUTER VISION

by

F. E. Dowell
Graduate Fellow
University of Illinois

J. C. Siemens
Professor
University of Illinois

L. E. Bode
Professor
University of Illinois

W. D. Wigger
Research Programmer
University of Illinois

For presentation at the 1987 Summer Meeting
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

Baltimore Convention Center
Baltimore, MD
June 28-July 1, 1987

SUMMARY:

A procedure using computer vision, a video camera, and fluorescent dye was developed to determine the incorporation characteristics of tillage tools. It was assumed that the dye represented herbicide. Image processing was used to store and analyze the incorporation profiles. The Kolmogorov-Smirnov statistical test was used to quantitatively compare incorporation profiles. The procedure was very quick and accurate.

KEYWORDS:

Computers, Cultivators, Herbicides, Tillage, Video, Vision.

American Society of Agricultural Engineers

St. Joseph, MI 49085-9659

HERBICIDE INCORPORATION ANALYSIS USING COMPUTER VISION

F.E. Dowell, J. C. Siemens, L. E. Bode, W. D. Wigger

ABSTRACT

A procedure using computer vision, a video camera, and fluorescent dye was developed to determine the incorporation characteristics of tillage tools. It was assumed that the fluorescent dye represented herbicide and would be displaced in a similar manner as herbicide applied to the soil. Image processing was used to store and analyze the incorporation profiles.

The Kolmogorov-Smirnov statistical test was used to quantitatively compare incorporation profiles. The procedure was very quick and accurate.

INTRODUCTION

Effective weed control is essential for profitable crop production. Herbicides can help provide this weed control when selected and applied properly. Proper use includes uniform application and, for some herbicides, uniform incorporation. Uniform incorporation maximizes the chance of weeds coming into contact with the herbicide and reduces crop damage due to high concentrations of the herbicide. Incorporation minimizes herbicide volatilization and photodecomposition. Environmental contamination due to herbicide in rainfall runoff is also reduced by incorporating the herbicide into the soil.

Uniform placement of herbicides results in the use of smaller amounts of chemical to control weeds and thus decreases weed control costs. Savings in money, energy, and time are direct benefits of uniform herbicide incorporation.

Conservation or reduced tillage systems dictate a need for single pass incorporation. Leaving residue on the surface with reduced tillage is effective in reducing water runoff, soil erosion, and moisture evaporation (Laflen et al., 1981). Herbicide usage often increases with conservation tillage because of reduced control of weeds by tillage (Epplin et al., 1983). Thus, uniform single pass incorporation is essential to the success of conservation tillage farming, both for weed control and improved soil and residue management.

A lack of knowledge of the reaction of soil to tillage tools (Schafer et al., 1984) dictates a need for two tillage passes to insure uniform herbicide incorporation. Single pass incorporation can result in non-uniform placement of the herbicide (Thompson et al., 1981), causing streaked weed control. Associated high concentrations of herbicide can cause crop injury. Precision incorporation is required for herbicides that are toxic to crops at rates required to provide adequate weed control. These herbicides must be precisely incorporated in areas not containing the crop seeds (Dowell, 1985).

The overall goal of this research is to specify design criteria or operating parameters for tillage tools to provide uniform, single pass herbicide incorporation. This paper reports the procedures used to trace soil displacement by incorporation tools, and the statistical method used to compare resulting incorporation profiles.

LITERATURE REVIEW

Tracing Techniques

The displacement of soil particles in response to a tillage tool must be understood to analyze how a herbicide is incorporated. To study the displacement of soil, an accurate procedure of tracing soil movement and comparing incorporation methods is required. Bucher et al. (1983), Morrison and Crowell (1952), Wooten et al. (1962), Sharp (1974), and Thompson et al. (1981) used a fluorescent dye and blacklights to trace soil displacement by tillage tools. Visual comparisons were made of the resulting dye distributions in the soil profiles.

Bode and Gebhardt (1969) and Read et al. (1968) extracted trifluralin and analyzed samples with a gas chromatograph. Read et al. (1968) used an analysis of variance to evaluate the uniformity of tracer incorporation. Wauchope et al. (1977) used copper sulfate as a tracer and analyzed soil cores with atomic absorption spectrophotometry.

Ladd and Futral (1966) and Morrison and Crowell (1952) used iron filings and iron balls as tracers and recovered them with a magnet after incorporation. Tollner, et al. (1986) used X-rays to view soil displaced by a tool. Soil failure cracks and differences in soil reactions due to moisture content could be viewed. Williford et al. (1968) incorporated fluorescent tracers and extracted the tracers from soil samples. The resulting extracts were analyzed with a fluorometer.

Hulbert and Menzel (1953) incorporated a radioactive phosphate tracer into the soil. Implement incorporation characteristics were determined by phosphate levels. Sorghum grain was also used as a tracer in other experiments. A coefficient of variation was used to describe uniformity of the tracer incorporation. James and Wilkins (1965) incorporated radioactive glass spheres. A scanning mechanism gave quantitative results by detecting the radioactive spheres. The scanning equipment was expensive and hazardous. Respirators, protective clothing, and a license from the Atomic Energy Commission were required.

Matthews (1970) extracted chloride tracers following incorporation. Numbered wood blocks (Gill, 1969) and pins placed in the soil have also been used. Salyani and Bowen (1983) incorporated dye coated sand particles into the soil and manually digitized black and white photographs of soil cross-sections.

These procedures used in the past took from one hour to four days to analyzed one soil cross-section.

Additional Analysis Techniques

Collier et al. (1979) used a transmission densitometer to analyze photographs of 2.5 cm squares of the soil profile. Smith (1955) used a mixing coefficient, expressed as the ratio of the standard deviation at zero mixing to the observed standard deviation of spot samples after mixing. The coefficient possessed the value of unity at no mixing and theoretically approached infinity as the mixed product became more uniform.

Brazee et al. (1968) developed a film scanner that converts an optical image to a time dependent electrical signal. Counts and measurements are made by computer. Equipment was expensive and designed specifically for this analysis.

Sistler et al. (1982) developed a method to analyze cards containing droplets from aerial application patterns. An image analyzer gave the areas and diameters of droplet images, counted the number of droplets, and calculated the number of droplets per unit area.

Salyani and Bowen (1985) developed a procedure to express the uniformity of dispersion of soil amendments quantitatively. The method accounts for the effects of spacing, location, and symmetry of points.

Many of the above methods used a visual assessment to compare the resulting profiles. Although some of the methods result in a number which represents the incorporation profile, none provide a valid statistical method to compare the incorporation characteristics of tillage tools.

HERBICIDE TRACING INVESTIGATIONS

Available methods of tracing the herbicide displacements were examined for accuracy, cost, and efficiency. Use of X-rays of a tracer were studied initially. It was proposed that a portable X-ray unit could be taken to the field and tracer distribution measured without disturbing the soil. A box constructed of 0.5 cm plexiglass having dimensions of 30 cm by 10 cm by 20 cm was constructed and tracers of sawdust, plastic shavings, iron filings, sand granules, gravel, and fluorescent dye were mixed in a clay loam soil and an artificial soil composed of Gooselake Fire Clay and mineral oil. The plexiglass box was then X-rayed from each direction. A special grid was used with the X-ray plates to enhance the image. Best results were obtained when the sample was X-rayed through the 10 cm section for 2 seconds at 90 kV without the grid. When the grid was in place, the soil was X-rayed for 5 seconds at 80 kV. Variations in the soil profile due to air pockets, non-uniform bulk density, and distortion due to projection of the image on the X-ray plates made identification of the tracers difficult. Each X-ray plate cost about $25. Thus, the X-ray method was determined to be inaccurate and expensive.

Water soluble fluorescent dyes were then examined. Thompson et al. (1981) showed that the incorporation pattern of fluorescent dye when applied to soil is similar to the incorporation pattern of herbicides. They photographed dye patterns immediately after application and painted the original patterns on plexiglass. Several weeks later, painted patterns on the plexiglass were placed to correspond to the original position of the incorporated dye in the soil. This correlation of dye position and weed control vividly illustrated the validity of this method.

It was proposed that incorporation of water soluble dyes and extracting dye from small sections of soil would indicate where the dye was placed after incorporation. Rhodamine B with high soil adsorption characteristics, and Rhodamine B Extra, which has a low soil adsorption tendency, were applied to the soil surface at 2500 ug/L, incorporated, allowed to set from 1 min to 48 hrs, and titrated with either 98% or 50% aqueous solution of methanol or ethanol. The resulting solution was analyzed using a Turner Model 111 fluorometer to determine the amount of dye extracted from a soil section. The amount of dye extracted was inconsistent with amounts varying from 20% to 80% and the procedure was very time consuming. Analysis of a single incorporation profile required up to 10 hrs to sample, titrate, and analyze. Therefore, this method was not used to analyze incorporation profiles in this study.

Powdered dyes were then examined. Fluorescent powdered dyes were spread on the soil surface and incorporated. A soil cross-section was cut and fluoresced with two blacklights. Different blacklights tried were two unfiltered General Electric F15T8-BL, two filtered F15T8-BLB, and two filtered F20T12-BLB blacklights. The unfiltered blacklights filtered out some visible light while the filtered blacklights filtered out all visible light. If more than one dye color was present, matching Kodak Wratten gelatin filters isolated one color at a time. The spectral curves of the dyes were matched to the spectrophotometric absorption curves of the filters. A No. 61 green, No. 92 red, or No. 98 blue filter was used to isolate green, red, and blue dye, respectively, while filtering out all other colors. The filters were placed in a 58 mm Kenko technical filter holder.

The resulting profiles were recorded using both 35 mm Ektachrome film (ASA 200) and a Sony Trinicon HVC-2800 video camera with a SLO-340 videocassette β1 recorder and a AC power adaptor. Photographs were taken with a f1.4 50 mm lens with exposure times of 5, 10, 20, and 30 s at a distance of 90 cm. Videos were taken with the aperture set completely open at all times. The 5 second exposure of the 35 mm film showed the most representative profile. The profiles on the photographs were compared to those on video and to the actual cross-section. The video camera consistently gave results that most closely matched the actual cross-section. The filtered blacklights fluoresced much more of the dye in the cross-section than the unfiltered blacklights. Use of the video camera proved to ba a fast, accurate, and economical method for recording soil profiles. Thus, this method was used to record cross-sections in the incorporation tests.

FIELD PROCEDURES

Initial tests were conducted in a soil bin at the University of Illinois Agricultural Engineering Department. Basic procedures used in later experiments were determined using the bin. Actual incorporation tests were conducted using a soil bin at Deere & Company Technical Center, Moline, IL and in the field at the Agricultural Engineering Research Farm, University of Illinois, Urbana, IL. Powdered fluorescent dyes and a video camera were used to record the incorporation characteristics of tillage tools.

A fluorescent dye was spread on the soil surface and then incorporated. A plexiglass plate was inserted into the soil and the soil cleared from the front of the plate. The plate was removed along with the dye that had been smeared as the plate was inserted. A vertical and horizontal axis containing 1 cm increments were placed along the right and lower sides of the profile. Fluorescent markers were used to mark the original soil surface and where the tool shanks had passed through the soil. A fluorescent string marked the soil surface after incorporation. The filtered blacklights and video camera were then positioned (Figure 1). A black plastic cover was placed over the cross-section and blacklights to eliminate visible light. The camera lens was placed through a hole in the plastic and focused (Figure 2).

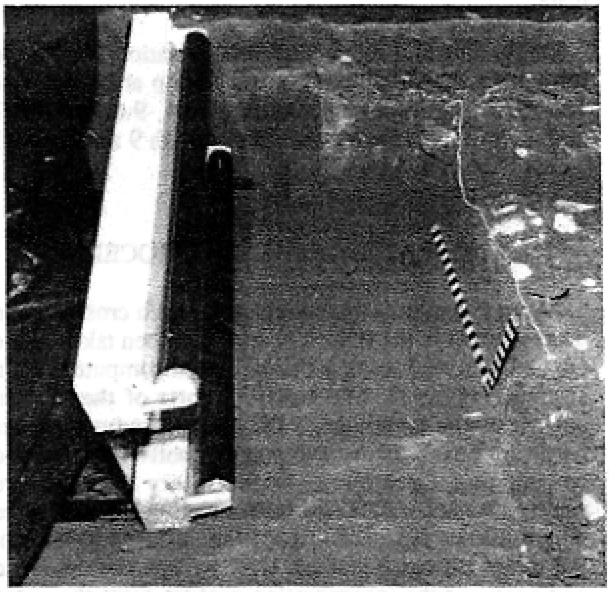

Fig. 1 - Blacklights used to fluoresce incorporated dye in excavated cross-section.

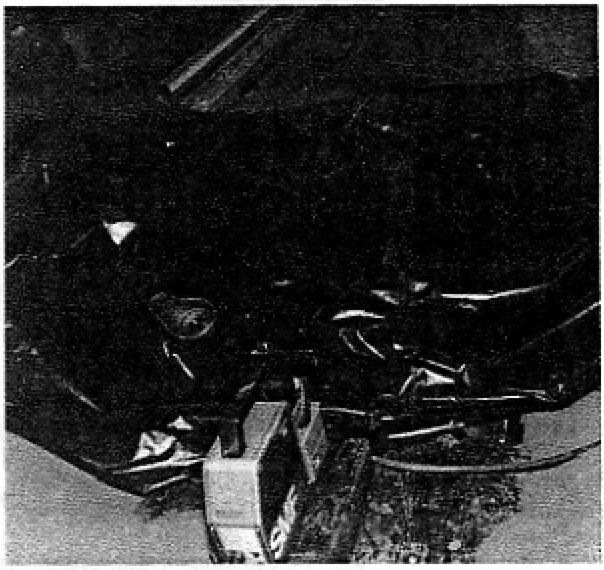

Fig. 2 - Video camera used to record the fluoresced cross-section. The lens is placed through a small opening in the black plastic that was placed over the excavated section.

Five counts on the video recorder were recorded of the axes and a tag showing the test number. A filter, if needed, was then placed over the lens and 10 additional counts filmed. Two additional replications of cross-sections were cut and filmed. The excavated soil was then replaced and the procedure repeated for additional tests.

Single and multiple shank incorporation tests were run with a 15 cm medium crown sweep at spacings of 10, 15, and 20 cm and speeds of 6.4, 9.6, and 12.9 km/hr. Multiple shanks were set up with 9 shanks on 3 rows of the cultivator.

INCORPORATION ANALYSIS PROCEDURE

About one minute of video tape for each cross-section was recorded in the field. The tape was then taken to the lab and analyzed using a PC/AT based computer vision system (Figure 3). The essential parts of the system consist of the computer, a PCVision Frame Grabber hardware board, and accompanying software produced by Imaging Technologies. A library of software routines was also obtained from Imaging Technologies which allows the user to program routines to control the image processing steps. User written routines read and analyzed the incorporation profiles from the video tape. Continuous footage of one cross-section was read from the video cassette tape and viewed in the video monitor of the image system until the image stabilized. The digitized image was then captured and stored on disk by the computer vision system. Another cross-section was then viewed and the process repeated until all recorded field data were transferred from video tape to disk files.

The stored cross-sections were later retrieved and analyzed. Routines were written to threshold the digitized image at an appropriate grey level to remove noise from the image. Another routine enabled the section to be further cleaned up by allowing the user to erase selected areas in the image. This resulted in an image containing only the dye particles and, if desired, the string marking the surface of the soil. Manipulation of the digitized cross-section occurred while comparing it to the actual cross-section viewed on a separate video monitor. This minimized removal of dye particles mistaken as noise in the digitized cross-section. Plots of the coordinates of the dye particles, using a computer spreadsheet, provided a hard copy of the resulting soil cross-section (Figure 4).

Statistical procedures were then performed on the digitized cross-section or on the coordinates of the dye particles stored on disk. A cross-section of soil can be transferred to disk and analyzed in less than five minutes.

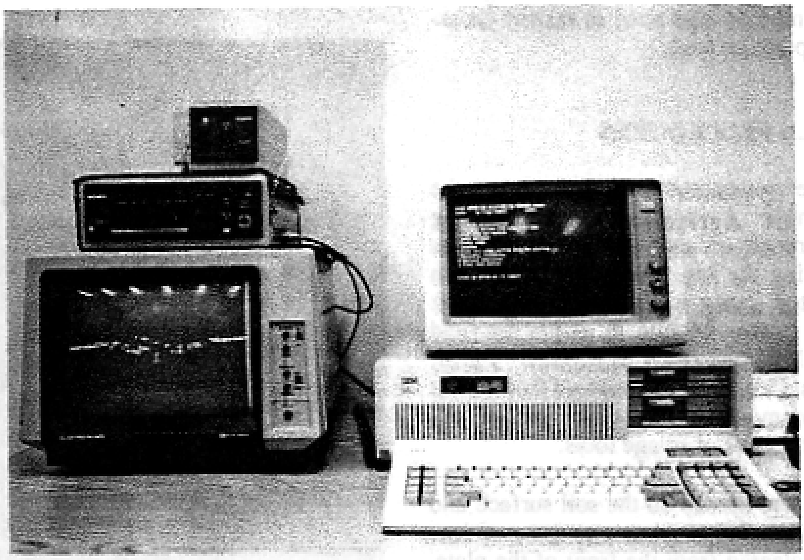

Fig. 3 - Computer vision system. Data is read into the computer from the video cassette recorder, digitized and stored for later analysis. The digitized and thresholded cross-section is shown on the left monitor, and the menu-driven program is shown on the right monitor.

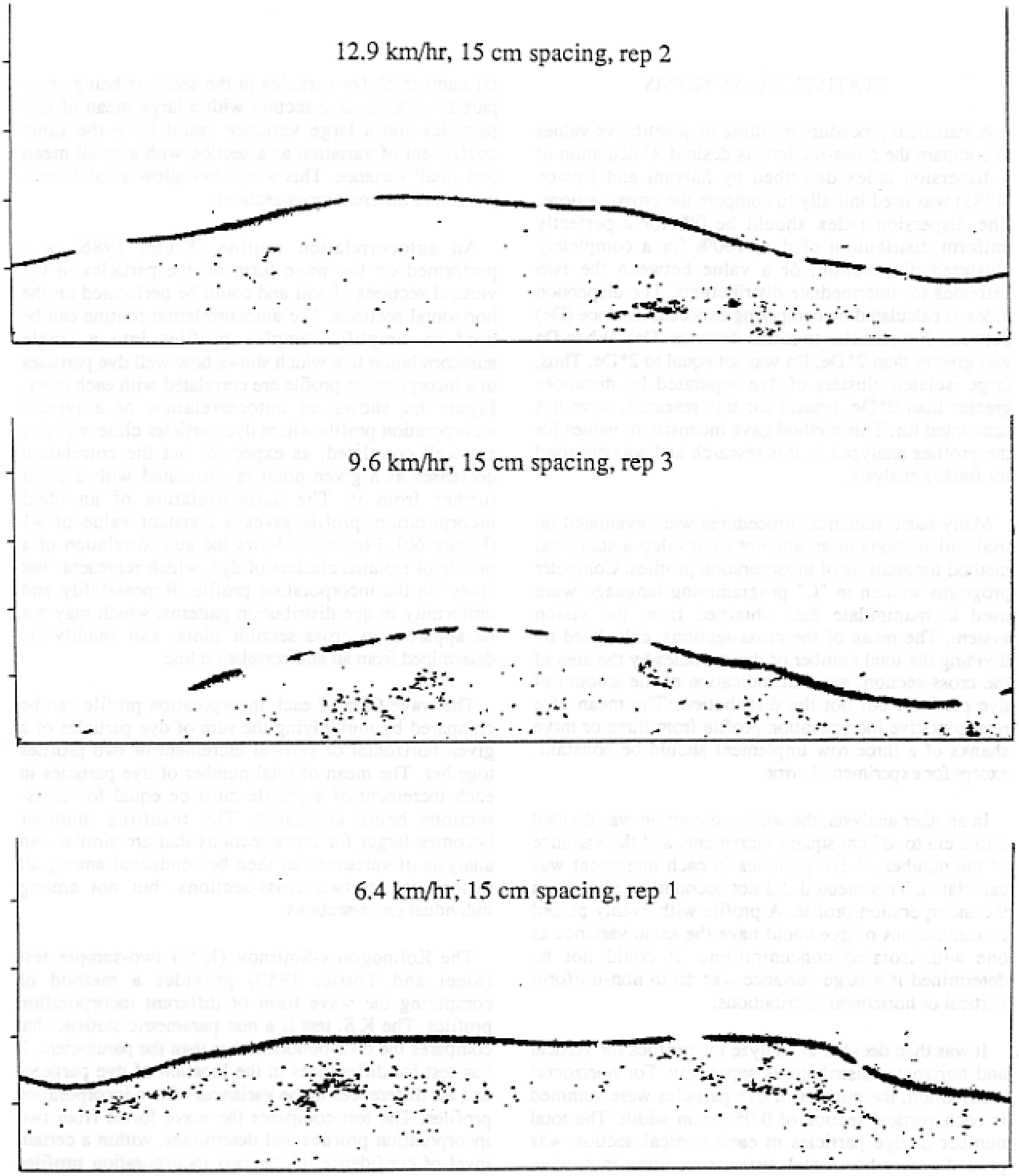

Fig. 4 - Dye incorporated with 15 cm sweeps in 45 cm wide cross-sections of soil. The solid line is a string marking the surface of the soil. Sweeps were run at a depth of 7.6 cm.

STATISTICAL ANALYSIS

A statistical procedure resulting in quantitative values to compare the cross-sections is desired. Calculation of a dispersion index described by Salyani and Bowen (1985) was used initially to compare the cross-sections. The dispersion index should be 0% for a perfectly uniform distribution of dye, 100% for a completely clustered distribution, or a value between the two extremes for intermediate distributions. The dispersion index is calculated by comparing expected distance (De) between dye particles to actual distance (Da). When Da was greater than 2*De, Da was set equal to 2*De. Thus, large isolated clusters of dye separated by distances greater than 2*De, typical for this research, were not accounted for. This method gave inconsistent values for the profiles analyzed in this research and was not used for further analysis.

Many basic statistical procedures were evaluated on trial soil sections in an attempt to develop a statistical method for analysis of incorporation profiles. Computer programs written in "C" programming language were used to manipulate data obtained from the vision system. The mean of the cross-sections, calculated by dividing the total number of dye particles by the area of the cross-section, gave an indication of the amount of dye particles but not the distribution. The mean of a representative incorporation profile from three or more shanks of a three-row implement should be constant, except for experimental error.

In another analysis, the soil cross-section was divided into 2 cm to .02 cm square increments and the variance of the number of dye particles in each increment was calculated. This method did not account for clusters in the incorporation profile. A profile with evenly placed concentrations of dye could have the same variance as one with isolated concentrations. It could not be determined if a large variance was do to non-uniform vertical or horizontal distributions.

It was then decided to analyze the profiles for vertical and horizontal distributions separately. For horizontal distribution, the number of dye particles were summed in each vertical section of 0.05 cm in width. The total number of dye particles in each vertical section was plotted versus horizontal distance resulting in a wave form (Figure 5). The variance about the mean of the plot provided an indication of the horizontal distribution of dye. Vertical distributions are analyzed similarly. Statistical comparisons could be made between the resulting variance of the data and the variance resulting from an ideal incorporation profile, if equal numbers of dye particles in the profiles are assumed.

A coefficient of variation can be calculated with this method, however, it must be emphasized that if the total number of dye particles in the sections being compared is not equal, a section with a large mean of dye particles and a large variance could have the same coefficient of variation as a section with a small mean and small variance. This would not allow a valid comparison of different cross-sections.

An autocorrelation routine (Klute, 1986) was performed on the wave form of dye particles in the vertical sections of soil and could be performed on the horizontal sections. The autocorrelation routine can be used to simplify complex profiles into a single autocorrelation line which shows how well dye particles in a incorporation profile are correlated with each other. Figure 6a shows an autocorrelation of a typical incorporation profile where dye particles close together are well correlated, as expected, but the correlation decreases as a given point is correlated with a point further from it. The autocorrelation of an ideal incorporation profile gives a constant value of +1 (Figure 6b). Figure 6c shows the autocorrelation of a profile of isolated clusters of dye, which represent "hot spots" in the incorporation profile. Repeatability and uniformity in dye distribution patterns, which may not be apparent in cross-section plots, can readily be determined from an autocorrelation line.

The wave form of each incorporation profile can be compared by multiplying the sum of dye particles of a given horizontal or vertical increment of two profiles together. The mean of total number of dye particles in each increment of a profile must be equal for cross-sections being compared. The resulting number becomes larger for cross-sections that are similar. An analysis of variance can then be conducted among all differences in two cross-sections, but not among individual cross-sections.

The Kolmogorov-Smirnov (K.S.) two-sample test (Steel and Torrie, 1980) provides a method of comparing the wave form of different incorporation profiles. The K.S. test is a non-parametric statistic that compares the distributions rather than the parameters. It can test for differences in the location of dye particles and for differences in the variances of two incorporation profiles. The test compares the wave forms from two incorporation profiles and determines, within a certain level of confidence, if the two incorporation profiles came from the same parent incorporation profile.

Two comparisons can be made with the K.S. method. First, each wave form can be compared with its mean. The resulting test statistic gives an indication of the variability in an incorporation profile. Second, each profile can be compared with another incorporation profile. The probability that both of these sections came from the same distribution can be calculated. This test

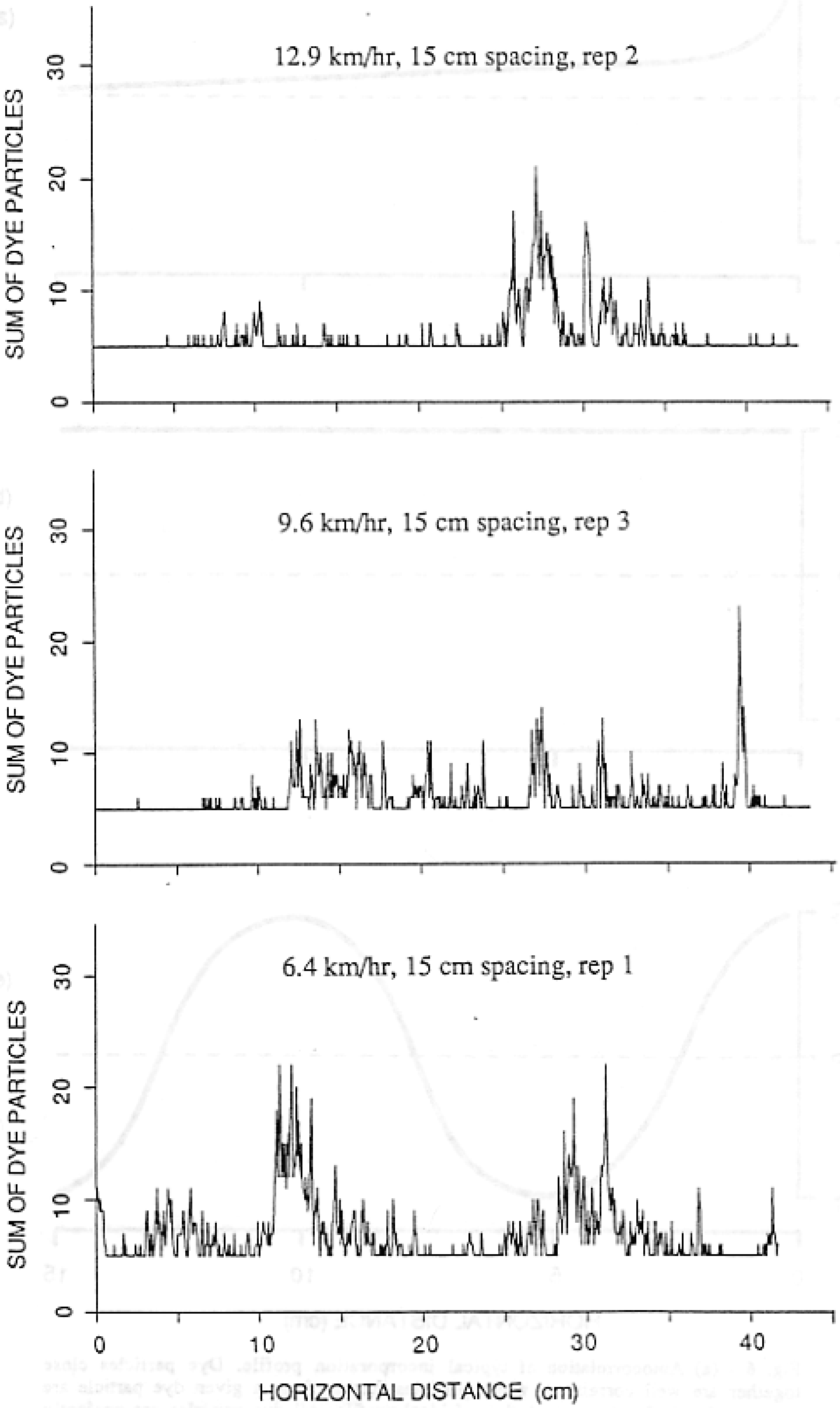

Fig. 5 - Dye particles were summed in each horizontal increment of .05 cm of the cross-section. Sweep spacings correspond to 0, 15, 30, and 45 cm on the horizontal axis.

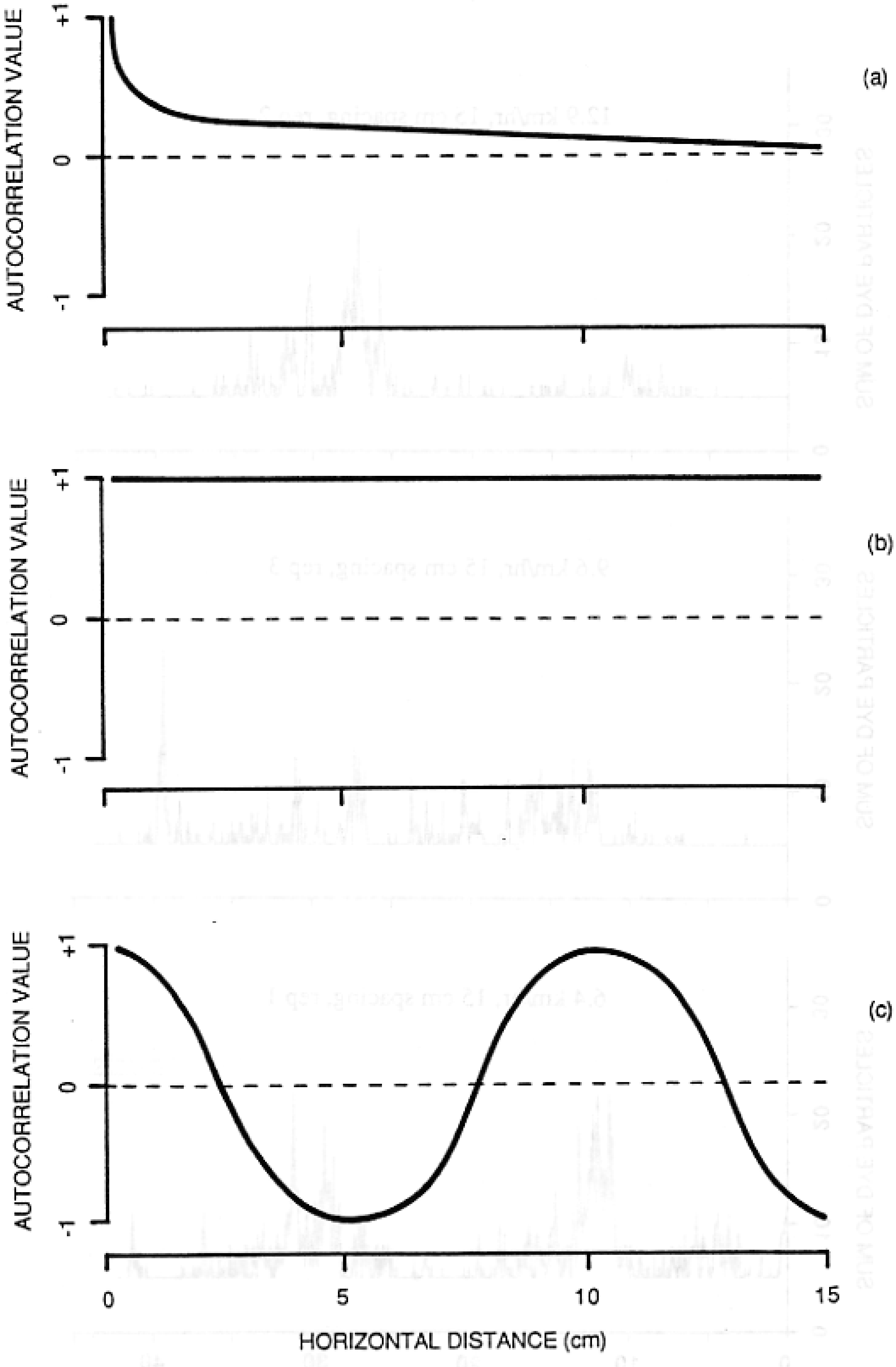

Fig. 6 - (a) Autocorrelation of typical incorporation profile. Dye particles close together are well correlated, while particles further from a given dye particle are less correlated. (b) Autocorrelation of ideal profile. All dye particles are perfectly correlated or perfectly distributed in the soil. (c) Autocorrelation of profile containing periodic "hot spots" or dye concentrations.

can be performed separately on the wave forms resulting from the horizontal and vertical distributions of dye.

The procedure used in the K.S. test is to first rank all observations together. Sample cumulative distribution functions are then calculated and the maximum difference (Dmax) in the sample distribution functions computed. Dmax is then compared to a calculated critical value at a chosen level of significance to determine if there is evidence to support the null hypothesis that the two samples come from the same parent distribution. Sample comparisons are shown in Table 1.

The data in Table 1 shows that the replications of 6.4 and 9.6 km/hr speeds came from the same parent distribution, which is expected if measurements are within experimental error. Further analysis shows that there is little difference in the 9.6 km/hr and 12.9 km/hr profiles, but that there are differences in the 6.4 km/hr and 9.6 km/hr profiles. These results indicate that tool speed has a highly significant (α = .01) effect on herbicide incorporation as speed is increased from 6.4 km/hr to 9.6 km/hr, but little effect is seen as speed is increased from 9.6 km/hr to 12.9 km/hr.

The K.S. method appears to be the best method for comparing the incorporation profiles of tillage tools. With this method, all incorporation profiles can be compared against an ideal incorporation profile and a test of significance performed. Also, two incorporation profiles can be compared to see if the profiles are the same, within a specified level of significance.

SUMMARY AND CONCLUSIONS

A procedure was developed to determine the location of a fluorescent dye when incorporated into the soil by a tillage tool. A video camera was used to determine the location of a surface applied dye after being incorporated. It was assumed that the fluorescent dye represented herbicide and would be displaced in a similar manner as herbicide applied to soil. Image processing was used to store and analyze the incorporation profiles. The procedure was very quick and accurate and will be used in subsequent incorporation tests.

Several statistical procedures were examined to analyze the incorporation profiles. The Kolmogorov-Smirnov statistical test provides a quantitative method of comparing the profiles.

Table 1 - Kolmogorov-Smirnov two-sample test results for incorporation profiles made with 15 cm sweeps on 15 cm effective shank spacings.

Comparison Speed (km/hr)	Rep	vs Speed (km/hr)	Rep	Dmax	Critical Value at α = .01
6.4	1	6.4	2	.03323	.07559
6.4	1	6.4	3	.04248	.07559
6.4	2	6.4	3	.05153	.07517
9.6	1	9.6	2	.03808	.07705
9.6	1	9.6	3	.06373	.07644
9.6	2	9.6	3	.02876	.07557
12.9	1	12.9	2	.03682	.07477
12.9	1	12.9	3	.07580**	.07417
12.9	2	12.9	3	.08221**	.07477
6.4[a]		9.6	1	.08488**	.07678
		9.6	2	.09551**	.07591
		9.6	3	.08920**	.07530
9.6[a]		12.9	1	.06710	.07527
		12.9	2	.05354	.07590
		12.9	3	.12890**	.07527

[a] Values averaged over replications.

** Comparisons are significantly different at α = .01

References

1. Bode, L. E. and M. R. Gebhardt. 1969. Equipment for incorporation of herbicides. Weed Science 17:551-555.

2. Brazee, R. D. , O. K. Hedden, and P. T. Keck. 1968. Flying-spot particle analyzer. USDA. C.A. No. 53. Revision 1.

3. Bucher, D. H., J. D. Long, and D. T. Sorlie. 1983. Seedbed preparation and chemical incorporation in conservation tillage. ASAE Paper No. 83-1521. American Society of Agricultural Engineers. St. Joseph, MI 49085.

4. Collier, J. A., T. H. Garner, and P. M. Burrows. 1979. Photographic evaluation of soil incorporation uniformity. ASAE Paper No. 79-1506. American Society of Agricultural Engineers. St. Joseph, MI 49085.

5. Dowell, F. E. 1985. Drill development for removal of herbicide treated soil. Masters Thesis. Oklahoma State University. Stillwater, OK 74074.

6. Epplin, F. M., T. F. Rice, S. J. Hanke, T. F. Peeper, and E. G. Krenzer, Jr. 1983. Economics of conservation tillage systems for winter wheat production in Oklahoma. Journ. of Soil and Water Conservation 38:294-297.

7. Gill, W. R. 1969. Soil deformation by simple tools. TRANSACTIONS of the ASAE 12(2):234-245.

8. Hulbert, W. C. and R. G. Menzel. 1953. Soil mixing characteristics of implements. Agricultural Engineering 53(10):702-705.

9. James, P. E. and D. E. Wilkins. 1965. An evaluation of radioisotope and fluorescent tracer techniques. TRANSACTIONS of the ASAE 8:199-202.

10. Klute, A. 1986. Methods of soil analysis. Part 1. Physical and mineralogical methods. Agron. Monograph, No. 9 (2nd Edition). American Society of Agron. Soil Science Society of America, Inc.

11. Ladd, T. B. and J. G. Futral. 1966. Technique and equipment for measuring the incorporation of chemicals into the soil. Georgia Agricultural Experiment Station Bulletin N. S. 173.

12. Laflen, J. M., W. C. Moldenhouer, and T. S. Colvin. 1981. Conservation tillage and soil erosion on continuously row-cropped land. Crop Production with Conservation in the 80's. pp121-132. American Society of Agricultural Engineers. St. Joseph, MI 49085.

13. Matthews, E. J. 1970. Chloride tracer evaluation of herbicide incorporation tools. TRANSACTONS of the ASAE 13:(1)64-66.

14. Morrison, H. E. and H. Crowell. 1952. Soil insecticide studies in Oregon. J. Econ. Ent. 45(6):1002.

15. Read, K., M. R. Gebhardt, and C. C. Day. 1968. Distribution of trifluralin in the soil when mixed with a disk harrow and power rotary cultivator. TRANSACTIONS of the ASAE 11:155-158.

16. Salyani, M. and H. D. Bowen. 1983. Computer aided technique for evaluation of soil amendment incorporation. ASAE Paper No. 83-1506. American Society of Agricultural Engineers. St. Joseph, MI 49085.

17. Salyani, M. and H. D. Bowen. 1985. Dispersion index as a means of comparing quality of mixing. International Conference on Soil Dynamics Proceedings. Auburn, AL.

18. Schafer, R. L., S. C. Yong, J. G. Hendrick, and C. E. Johnson. 1984. Control concepts for tillage systems. Soil and Tillage Research 4:313-320. Elsexier Science Publishers. B. V., Amsterdam.

19. Sharp, R. B. 1974. A method of tracing the initial placement of soil-applied herbicides. J. Agr. Eng. Res. 19:93-95.

20. Sistler, F. E., P. A. Smith, and D. C. Rester. 1982. An image analyzer for aerial application patterns. TRANSACTIONS of the ASAE 26(2):885-887.

21. Smith, J. L. 1955. Mixing chemicals with soil. Industrial and Eng. Chemistry. 417(11):2240-2244.

22. Steel, R. G. D. and J. H. Torrie. 1980. Principles and procedures of statistics. A biometrical approach. McGraw Hill.

23. Thompson, L., Jr., W. A. Skrock, and E. O. Beasley. 1981. Pesticide incorporation - distribution of dye by tillage implements. N. C. Agr. Ext. Ser., AG 250. 32 p.

24. Tollner, E. W., Verma, B. P. and J. M. Cheshire. 1986. Observing soil-tool interactions and soil organisms using X-ray computer tomography. ASAE Paper No. 86-1042. American Society of Agricultural Engineers. St. Joseph, MI 49085.

25. Wauchope, R. O., J. M. Chandler, and K. E. Savage. 1977. Soil sample variation and herbicide incorporation uniformity. Weed Science 25(2):193-196.

26. Williford, J. R., O. B. Wooten, and W. C. Barrentine. 1968. Fluorometric analysis for evaluation of soil incorporation. Weeds 16:372-377.

27. Wooten, O. B., C. G. McWhorter, and C. D. Ranney. 1962. Underground application of herbicides and fungicides. Agr. Eng. 44:30-34.