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# Methods for measuring soil velocities caused by a sweep

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A field experiment was conducted to measure surface soil velocity and to determine the relation between soil aggregate velocities at the tool surface and at the soil surface.

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## Introduction

Soil movement caused by a tillage tool may rearrange soil aggregates. Such rearrangement would affect weed control by the mixing of herbicides and alteration of weed seed depth in the soil. The ability to measure soil velocities during tool passage would help to predict soil movement caused by the tool.

Researchers have used various techniques to track soil movement by tillage. Some techniques measure quantitative soil movement by noting final displacement differences of a marker compared with position before tillage. The marker is assumed to move with the soil and to be a reliable measure of

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soil movement. Nichols and Reed (1934) reported the use of small marker blocks by Wallace Ashby of the USDA Bureau of Agricultural Engineering. Ashby studied soil displacement by a moldboard plow. He buried small blocks in known locations before tillage, and after tillage measured block locations to determine soil movement. Payne (1956) used a layer of lime as an indicator of soil movement. To investigate soil movement resulting from tool action, Gill (1969) used marker pins with different colored heads placed in the soil.

To investigate the effect of moldboard shapes on high-speed plowing, Söhne (1959) developed a method of measuring soil aggregate paths across the tool surface during tillage by means of scratch marks made in a white nitrocellulose lacquer. Söhne (1960) noted that the magnitude of lateral transport of the soil depends upon the lateral directional angle of scratch marks at the edge of the moldboard surface, where soil exits the tool.

O'Callaghan and McCoy (1965) also investigated soil flow across moldboard plow shapes. Again, white nitrocellulose lacquer was used. The researchers cited Söhne's (1959) use of lacquer and that he had found the coefficient of friction between lacquer and soil to be similar to that between steel and soil. They observed that 18 m of plowing produced a clear pattern of scratch marks.

O'Callaghan and McCoy (1965) measured scratch paths (in $x$, $y$ and $z$ coordinates) across various moldboard plow shapes. Coordinates were fitted to curves for which $y$ or $z$ displacements were polynomial functions of the displacement in the travel direction, or $x$. These expressions were differentiated twice with respect to time to determine acceleration in $y$ and $z$ directions. An important assumption was that soil velocity in the direction of travel did not change. The acceleration of soil particles did not change predictably with the square of travel speed because the soil path also changed. Soil was lifted higher as speed increased.

Tollner et al. (1986) used X-ray techniques to study soil displacement by a tool. Dowell et al. (1988) studied field-cultivator speed and sweep spacing effects on herbicide incorporation. Fluorescent dye coated granules were incorporated in soil, and their distribution was analyzed with computer image analysis of a videotape of the soil profile.

These previous studies have measured soil movement either as the difference between initial and final conditions before and after tool passage (without identifying actual soil movement on the tool), or, if soil movement on the tool was quantified, it was limited to a measurement of the movement at the soil–tool interface (i.e. the tool surface). Obviously during tillage soil aggregates are moving throughout the entire soil slice on the tool. Most physical soil changes caused by tillage must occur during tool passage. A method to measure soil movements during tillage in another section of the soil slice would help to illuminate changes in the soil caused by the tool's action. This study describes a method to measure soil movement during tillage at a second surface, the soil surface, and compares the values found at this surface with those measured at the soil–tool interface for changes in tool geometry and operation.

Measurement of soil aggregate movement on this second surface can yield additional information of the effects of changes in tool geometry and operation during manipulation of the soil by tillage. Effective design and operation of tillage tools can be enhanced by understanding relations between tool shape and movement and relative soil aggregate movements during tool passage.

Although a sweep has relatively simple geometry, it is frequently used to bury small weeds or seed and mix plant nutrients or herbicide within a shallow surface layer. Measurement of movements at the soil surface are an initial step to discovering how a sweep may incorporate surface applied crop inputs into a shallow layer. If a relation exists between soil movement at the soil surface and at the tool surface, soil movement may be predicted by measurement at only one of the surfaces. Then development of a simplified soil–tool model based on uniform relative movements between aggregates on the tool might be justified. If no such relationship exists, relative soil aggregate movements within the soil block may create a random mixing action. In this case a soil–tool model should assume different soil movements within different regions of the soil slice. Harrison (1990) found the shape of soil on a tool face to be different than that proposed by existing models. Knowledge of soil movements in addition to shape may help model development. In particular, different geometry in the nose and stem area of a sweep may cause a different soil movement from that which occurs near the wing tip. Objectives of this experiment were, during tillage with a sweep: to determine the effect of sweep rake angle, speed, and depth on soil aggregate velocities at the soil surface as estimated by markers; to determine these effects on soil aggregate flow paths at the soil–tool interface and at the soil surface; to determine whether a relation exists between soil aggregate flow path at the soil–tool interface and at the soil surface; to determine by use of markers if aggregate velocity of surface soil at the nose of the sweep differs from that at the wing tip.

## Materials and methods

Soil aggregate movements on cultivator sweeps were measured in a randomized complete block field experiment. Within each block, factorial combinations of three sweep rake angles (13.5°, 16°, and 44°), three speeds (1.4, 1.9, and 2.5 m $s^{-1}$) and two depths (50 and 100 mm) were evaluated.

One of two different soil types, Canisteo silty clay loam (fine loamy, mixed (calcareous), mesic Typic Haplaquolls) or Clarion loam (fine loamy, mixed, mesic Typic Haplaquolls), was the predominant soil in each experimental block. Each block was tilled in 1 day. Soil moisture conditions in the surface 100 mm ranged from 0.115 to 0.247 Mg $Mg^{-1}$. Soil bulk density in the surface

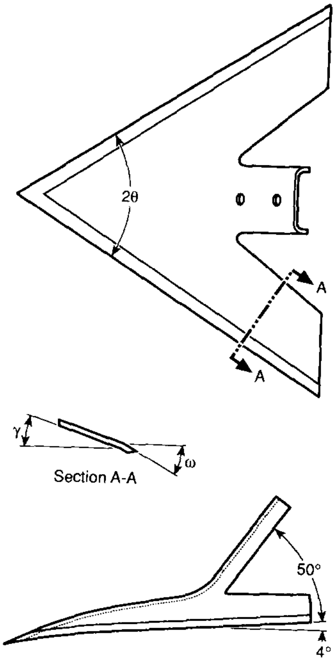


Fig. 1. Sweep geometry with cutting edge inclined to travel direction by angle $\theta$ and predominant sweep wing rake angle $\gamma$. $\omega$ is edge rake angle. Sweep stem angle used is 50°. Sweep pitch is 4°.

100 mm, measured by means of gravimetric analysis of samples from a 16 mm diameter soil probe, ranged from 1.36 to 1.59 Mg $m^{-3}$.

A flat tillage sweep can be thought of as two planes joined together at a junction line which projects to the point of the sweep (Fig. 1). The cutting edge of each plane is inclined in the direction of travel by an angle, $\theta$, which equals half the nose angle, $2\theta$, formed by the sweep's cutting edges. Further, each plane has a rake angle, $\gamma$, perpendicular to the cutting edge (Fig. 1).

Two methods were used to estimate soil aggregate velocities during sweep tillage, one at the tool surface and one at the soil surface.

*Velocity measurements at soil–tool interface*

The interface of soil and tool is at the bottom of the main soil slice being manipulated by the tool. Scratch paths on a painted surface were used to measure the direction of soil velocity. A pilot experiment was conducted with different formulations and colors of paint to allow judgment of the production of suitable scratch marks. Red or blue paint on the tool surface produced more visible scratch marks than did white or dark earth tones.

Two sweeps were operated in each experimental plot. Four paint formulations were used, one on each sweep wing, to facilitate measurement of scratch marks. Paints chosen were red lacquer, red enamel, red acrylic and blue automotive upholstery paint.

Paints were sprayed on the tool surface and allowed to dry for approximately 2 min before tillage. Sweeps were removed immediately after tillage, and soil was gently brushed away. Photographs of each sweep were taken from a fixed position directly above the sweep and later were analyzed to determine the direction of soil flow.

Scratch path angles relative to the sweep centerline were measured on two different sweep wings for each experimental plot. Parallax in reading of scratch path angles from two-dimensional photographs was corrected by use of known angles marked on the face of each sweep wing.

To estimate the magnitude of aggregate velocities on the bottom of the soil slice, it was assumed (as by O'Callaghan and McCoy, 1965) that relative soil velocity with respect to the tool parallel to travel direction was a constant equal to tool speed. This assumption seems reasonable from a continuity standpoint. Consider a tool that has been tilling soil for some time so that the amount of soil on the tool has reached a constant value (subject to random fluctuation about a mean). The flow rate of soil entering the tool in the travel, i.e. the $x$, direction must equal the flow of soil leaving the tool in the travel direction. If it does not, soil will either continue to build up or dissipate in front of the tool.

The choice of magnitude for soil aggregate velocities at the bottom of the soil slice affects only the magnitude of these velocities with respect to the tool, and does not affect their direction. Correlation coefficients used to determine if a relation exists with velocities at the soil surface is a test of whether or not flow directions are parallel. Scalar multiplication of the velocities should not affect a correlation test.

A geometric development of velocities at the bottom of the soil slice as measured from the scratch angles is shown in Fig. 2. A Cartesian coordinate system is oriented with the $xy$ plane parallel to the travel direction and $xz$ plane including the sweep cutting edge. Plane ACN is a trihedral wedge, the sweep wing surface. Angle BCN is wing rake angle, $\gamma$, and angle CAO is $\theta$, equal to half the sweep nose angle. Line AN is a scratch mark and the scratch angle, $\alpha$, is measured as the angle between line BA, the projection of the scratch mark on the plane containing the sweep cutting edges, and the $x$ axis (Fig. 2).

The lateral soil velocity component, BO, is expressed as:

$$\mathrm{BO} = \mathrm{AO} \tan \alpha \tag{1}$$

To determine the vertical velocity component, BN, note that $\mathrm{AB} = \mathrm{AO}/\cos \alpha$, $\mathrm{BC} = \mathrm{AB} \sin(\theta - \alpha)$, and $\mathrm{BN} = \mathrm{BC} \tan \gamma$. Substituting

$$BN = AO \sin(\theta - \alpha) \tan\gamma / \cos\alpha \quad (2)$$

Assuming the amount of soil on the wing reaches a constant value, the $x$ velocity component of soil, AO, equals tool speed during the time soil is moving along line AN. By substituting into eqns. (1) and (2), vertical and lateral soil velocities are given in eqns. (3) and (4):

$$yvlb = (\text{tool speed})(\cos\alpha)^{-1} \sin(\theta - \alpha) \tan\gamma \quad (3)$$

$$zvlb = (\text{tool speed}) \tan\alpha \quad (4)$$

where $yvlb$ is soil velocity parallel to $y$ axis (m $s^{-1}$), $zvlb$ is soil velocity parallel to $z$ axis (m $s^{-1}$), speed is tool speed (m $s^{-1}$), $\alpha$ is scratch angle, $\gamma$ is rake angle, and $\theta = 0.5$ (nose angle).

Sweep pitch (Kydd and Boyden, 1988) was set at 4° from the horizontal during the experiment. This had the effect of rotating the $xz$ plane about the $z$ axis. Thus the actual velocity in the vertical direction is increased slightly by a sweep pitch of 4°. This additional lift factor is approximately speed × [tan(pitch)]. Because the axis of rotation is the $z$ axis, the soil velocity component perpendicular to the travel direction is negligibly affected by sweep pitch. Sweeps had a slightly steeper rake angle at the cutting edge, $\omega$ (Fig. 1). Scratch paths were not visible on this part of the sweep.

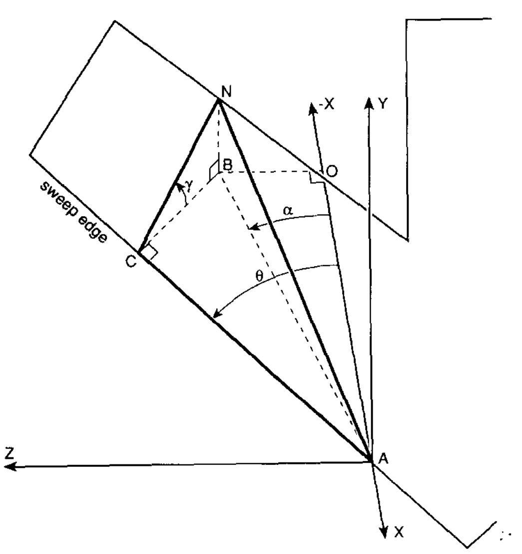


Fig. 2. Soil aggregate flow path, AN, on the sweep plane.

*Velocity measurement at soil surface*

Soil aggregate velocities at the soil surface were measured in terms of the movement of brightly colored wooden blocks placed on the surface and assumed to be moving with the soil. Observational equipment was mounted on a toolbar assembly behind a tractor with 2.3 m wheel spacing. Two 410 mm sweeps with similar geometry were mounted on 760 mm spacing about the tractor centerline on the rear bar of a toolbar assembly (Figs. 3 and 4). Gage wheels mounted on the rear toolbar controlled sweep depth.

Surface soil movement was recorded with a video camcorder mounted on the front bar of the toolbar assembly, 1.6 m directly in front of the horizontal midpoint of one of the inner sweep wings (Fig. 4). In addition to measuring the velocities in the two dimensions directly visible to the camcorder, measuring the velocities of the blocks in the travel direction was desirable. To accomplish this a 230 mm×300 mm mirror was mounted at a 45° angle directly above the sweep wing in the camcorder field of view (Figs. 3 and 4).

The measurement capabilities of the camcorder and of the wooden blocks were tested in pilot experiments of sweeps operating in snow and in soil. Differently sized wooden cubes and variously colored paints on the cubes were tested to determine which combinations might best be observed and mimic soil flow. The experiments showed that blocks as small as 10 mm cubes could be recorded moving with the soil flow. The mass of such wooden cubes corresponds to that of dry, spherically shaped soil aggregates 9 mm in diameter

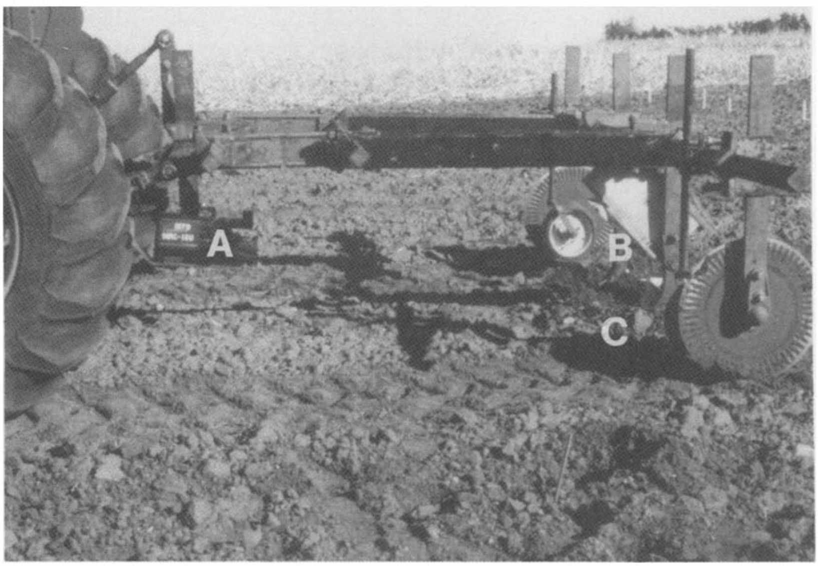


Fig. 3. Toolbar assembly. A, video camcorder; B, mirror; C, sweep.

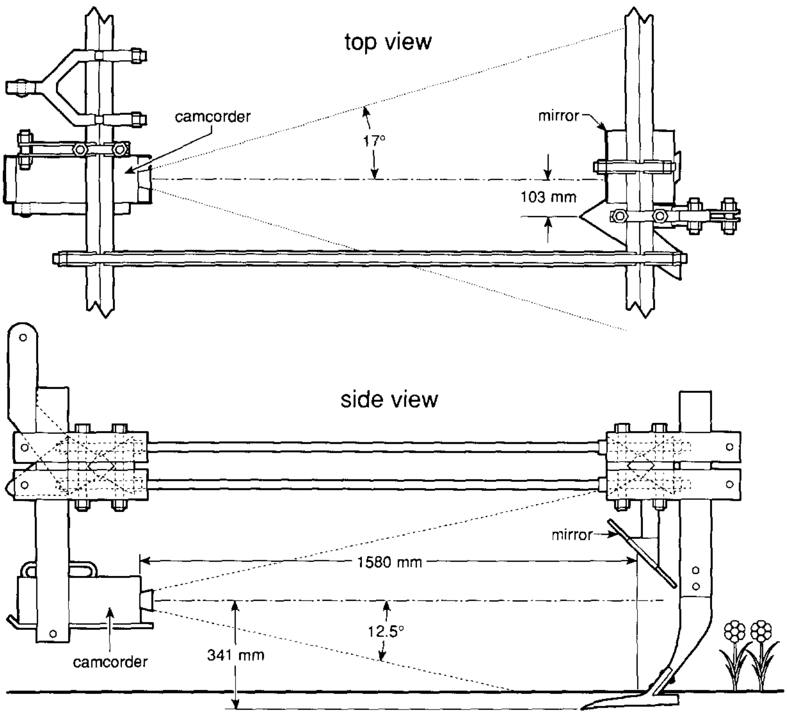


Fig. 4. Toolbar assembly showing location of video camcorder with respect to sweep and overhead mirror. Also shown is video camcorder field of view.

(assuming 1.4 Mg $m^{-3}$ bulk density). Wooden cubes (10 mm) painted white and two fluorescent colors, yellow and orange, were used.

Before tillage of each experimental plot, eight cubes in alternating colors were placed on 50 mm centers on the soil surface in a line perpendicular to the direction of travel and centered on the sweep wing to be observed.

Soil aggregate velocities, as measured by the blocks or scratch paths, were considered oriented in a three-dimensional space with the $x$ axis parallel to travel direction, the $y$ axis vertical, and $z$ axis in a horizontal plane perpendicular to travel direction.

The videotape was used to facilitate measurement of block velocities by location of each block's positions in consecutive frames of videotape taken at 1/30 s intervals. Block positions in the videotape were adjusted for parallax by computing a block distance from the camcorder lens and its position from the lens centerline (Hanna et al., 1991).

A transparent graph was used to read unit dimension values on the video screen projecting the videotape. These unit graph values were changed to dimensions in the $x$, $y$, and $z$ directions from the sweep point. The difference between *x, y*, and *z* coordinates in consecutive frames of the videotape was used to determine wooden block velocity.

Because of variations in block movement at different positions between the point of the sweep and the wing tip, the velocity of each marker block was considered to represent only that section of the sweep bounded by midpoints between the blocks. Blocks nearest the sweep point or wing tip represented sections bounded at one end by the point (or wing tip) and at the other end by the midpoint between blocks. In this manner, a weighted average soil velocity was computed for the soil surface velocity across the half of the sweep viewed by the camcorder. To compare velocity difference between the nose and wing tip sections, the sweep wing was divided in half and the weighted velocity computed for the half bounded on one side by the nose was compared with the half bounded on one side by the wing tip.

## Results and discussion

Qualitatively, the surface of the soil, as observed by block movement on the videotape, moved in one of two modes. These modes were (1) V-flow, with blocks staying atop or near the soil surface and generally moving upward and laterally in the shape of one leg of the letter V, and (2) snowplow, with blocks initially moving upward and subsequently being buried in a wave of soil. The mode of block and soil aggregate movement seemed unrelated to tool geometry, speed, depth, or soil conditions. Only about one-fourth of the wooden blocks in three of the experimental blocks were visible on the surface after passage of the tool.

Because of the variability of block movement throughout the trajectory of V-flow, as well as the burial of blocks near the output section of the sweep, block movements used in the analysis were confined to those beginning near the first soil-surface failure plane, i.e. where the surface had begun to deform. This represented soil velocity from the intake section of the tool to approximately one-third to one-half of the distance up the sweep wing. Koolen and Kuipers (1983) have described these areas as the intake and the (initial) main flow sections of the tool. Predominantly because some blocks were covered quickly in the snowplow mode, 62 usable observations of surface soil velocity were obtained from 90 experimental plots.

Velocity components in the *x, y, z* directions at the soil surface as measured by the blocks are shown in Table 1 for each main factor. Usable observations occurred randomly among treatments. Because not all plots had observations, standard errors were computed for each factor/velocity combination and used to determine statistical differences. Absolute surface soil velocity parallel to the travel direction increased with increasing speed and sweep rake angle. Absolute surface soil velocity in a horizontal plane perpendicular to the travel direction increased with increasing speed.

Table 1
Mean soil surface velocity components (m $s^{-1}$) and standard errors (SE) for three sweeps, three travel speeds, and two depths

| Factor | No. of observations | *xvlt* | | *yvlt* | | *zvlt* | |
|---|---|---|---|---|---|---|---|
| | | Mean | SE | Mean | SE | Mean | SE |
| Rake angle (°) | | | | | | | |
| 13.5 | 20 | 0.34[a] | 0.11 | 0.49 | 0.06 | 0.40 | 0.04 |
| 16 | 19 | 0.76[ab] | 0.23 | 0.51 | 0.09 | 0.46 | 0.05 |
| 44 | 23 | 0.94[b] | 0.20 | 0.46 | 0.09 | 0.41 | 0.07 |
| Speed (m $s^{-1}$) | | | | | | | |
| 1.4 | 20 | 0.20[a] | 0.13 | 0.28 | 0.06 | 0.34[a] | 0.05 |
| 1.9 | 23 | 0.64[ab] | 0.15 | 0.52 | 0.05 | 0.40[ab] | 0.06 |
| 2.5 | 19 | 1.27[b] | 0.23 | 0.65 | 0.11 | 0.53[b] | 0.05 |
| Depth (mm) | | | | | | | |
| 50 | 33 | 0.89 | 0.17 | 0.50 | 0.08 | 0.42 | 0.04 |
| 100 | 29 | 0.46 | 0.13 | 0.47 | 0.05 | 0.41 | 0.05 |

Values in each column within each factor followed by a different letter are significant at the $\alpha = 0.05$ level.
*xvlt*, soil aggregate velocity parallel to travel direction at soil surface; *yvlt*, vertical soil aggregate velocity at soil surface; *zvlt*, soil aggregate velocity perpendicular to travel direction in horizontal plane at soil surface.

Using the Cartesian velocity components, angles made by soil flow with a horizontal plane and projected on to the *yz* plane were determined at the soil surface and tool surface (Table 2). Similarly soil surface velocity components were used to determine the angle of soil surface flow with the travel direction projected on to a horizontal (*xz*) plane. A comparable angle on the tool surface was not computed since it was assumed that absolute soil velocity along the travel direction was zero. Standard errors were computed for each factor. Surface soil flow had greater variance than flow at the tool surface. Flow at the tool surface had a greater ratio of vertical to lateral movement than did flow at the soil surface. Soil flow path along the tool surface became more vertical as sweep rake angle increased.

Scratch mark data available from all 90 experimental plots were used to compare angles of soil flow with a horizontal plane projected on to the *yz* plane (Table 3). Because a complete data set was available, variance of the entire set was used to compute least significant differences and confirm a steeper flow path with larger sweep rake angle.

Because of missing observations, data were pooled from all sweep, speed, and depth combinations (62 with both soil surface and soil–tool interface data) to determine whether a relation exists between velocities measured on the top and on the bottom of the soil slice flowing over the tool. Correlation

Table 2
Angle of soil flow at soil surface and tool surface projected on to *yz* plane and angle of soil flow at soil surface projected on to *xz* plane for each main factor

| Factor | No. of observations | Projected angle of soil flow (°) | | | | | |
|---|---|---|---|---|---|---|---|
| | | *yz* plane[a] | | | | *xz* plane[b] | |
| | | Soil surface | | Tool surface | | Soil surface | |
| | | Mean | SE | Mean | SE | Mean | SE |
| Rake angle (°) | | | | | | | |
| 13.5 | 20 | 49 | 4 | 71[a] | 2 | 22 | 12 |
| 16 | 19 | 42 | 6 | 81[b] | 2 | 40 | 7 |
| 44 | 23 | 46 | 8 | 88[c] | 1 | 16 | 6 |
| Speed ($m\ s^{-1}$) | | | | | | | |
| 1.4 | 20 | 37 | 7 | 82 | 3 | 10 | 12 |
| 1.9 | 23 | 52 | 5 | 80 | 2 | 29 | 7 |
| 2.5 | 19 | 48 | 6 | 80 | 2 | 36 | 6 |
| Depth (mm) | | | | | | | |
| 50 | 33 | 46 | 5 | 80 | 2 | 20 | 7 |
| 100 | 29 | 46 | 5 | 81 | 2 | 31 | 8 |

Values in each column within each factor followed by a different letter are significant at the $\alpha=0.05$ level.
[a]Angle of soil flow with horizontal projected on to *yz* plane.
[b]Angle of soil flow with travel direction projected on to *xz* plane.
SE, standard error.

coefficients of measured velocities are shown in Table 4 for data from all treatment combinations. When the hypothesis that the correlation coefficients in Table 4 were zero was tested, none of the coefficients for the variables listed had a probability smaller than 0.10. As suggested by flow directions in Table 2, measurements show no correlation between soil aggregate velocities at the soil surface and those at the soil–tool interface. This indicates that soil flow paths at the soil surface and those at the soil–tool interface are not parallel.

Thirty-six experimental plots had marker block velocity data from both the sweep half closest to the nose and the half closest to the wing tip. Pooled data from these plots for all sweep, speed, and depth combinations indicated that the $z$ (lateral) velocity component at the soil surface was 0.42 $m\ s^{-1}$ for the nose sweep half versus 0.34 $m\ s^{-1}$ for the wing tip sweep half. The $y$ (vertical) velocity component at the soil surface was 0.70 $m\ s^{-1}$ for the nose sweep half versus 0.42 $m\ s^{-1}$ for the wing tip sweep half. A paired statistical comparison indicated a significant difference at an $\alpha=0.001$ level for vertical velocity.

Table 3
Angle of soil flow at tool surface projected on to *yz* plane for each main factor (data from all experimental plots)

| Factor | Projected angle in *yz* plane[a] (°) |
|---|---|
| Rake angle (°) | |
| 13.5 | 73[a] |
| 16 | 80[b] |
| 44 | 86[c] |
| LSD ($\alpha=0.05$) | 4 |
| Speed ($m\ s^{-1}$) | |
| 1.4 | 79 |
| 1.9 | 80 |
| 2.5 | 80 |
| LSD ($\alpha=0.05$) | 4 |
| Depth (mm) | |
| 50 | 80 |
| 100 | 79 |
| LSD ($\alpha=0.05$) | 3 |

Values in each column within each factor followed by a different letter are significant at the $\alpha=0.05$ level.
[a]Angle of soil flow with horizontal projected on to *yz* plane.
LSD, least significant difference.

Table 4
Correlation coefficients between soil surface and soil–tool interface velocity components for combined data from three sweeps, three travel speeds, and two depths

| | zvlb | yvlt | zvlt |
|---|---|---|---|
| yvlb | −0.19 | 0.10 | 0.15 |
| zvlb | | −0.09 | 0.14 |
| yvlt | | | −0.09 |

*zvlb*, Soil aggregate velocity perpendicular to travel direction in horizontal plane at soil–tool interface (mean = 0.08 $m\ s^{-1}$, standard error = 0.01 $m\ s^{-1}$). *yvlt*, Vertical soil aggregate velocity at soil surface (mean = 0.48 $m\ s^{-1}$, standard error = 0.05 $m\ s^{-1}$). *zvlt*, Soil aggregate velocity perpendicular to travel direction in horizontal plane at soil surface (mean = 0.42 $m\ s^{-1}$, standard error = 0.03 $m\ s^{-1}$). *yvlb*, Vertical soil aggregate velocity at soil–tool interface (mean = 0.65 $m\ s^{-1}$, standard error = 0.05 $m\ s^{-1}$)

Greater vertical velocity near the sweep nose may be the result of the influence of sweep stem and mounting shank on the soil travel path.

The observed snowplow flow mode, burial of three-fourths of the wooden marker blocks at the soil surface, and greater variance in flow path may be caused by the absence of an upper confining layer above the soil. Because there is no confining layer above the soil surface, flow paths at the soil surface may differ from those at the soil–tool interface where soil is confined by soil above and by tool surface beneath. The mixing of soil because of divergent flow paths and observed burial of surface blocks agreed with the effectiveness of sweeps for herbicide incorporation (Dowell et al., 1988).

The soil surface flow direction was approximately balanced between lateral and vertical flow, while soil flow at the soil–tool interface was more vertical. The vertical component of soil surface velocity was greater at the nose than at the wing tip. This flow suggests twisting and shearing of the soil slice as it moves up the sweep wing, although when flow paths from each plot were compared, no relationship existed between flow at the top and bottom of the slice.

Soil surface velocity had a measurable component parallel to and positive with the travel direction which increased with speed and sweep rake angle. If the assumption is correct that soil exiting the tool in the travel direction must equal soil entering the tool, then unless soil bulk density on the tool increases or the cross-sectional area of soil flow increases, other parts of the soil flow slice must have absolute velocity in an opposite direction.

## Conclusions

Tool geometry (rake angle) and operation (speed) have some effects on surface soil aggregate velocities. Surface soil aggregate velocity parallel to the travel direction, as estimated by markers during tillage with a cultivator sweep, increased with increasing speed and rake angle. Surface soil aggregate velocity in the lateral direction (horizontal and perpendicular to the travel direction) increased with tool speed. Such information implies that increased tool speeds move surface soil further laterally and forward while increased rake angle also moves surface soil further forward.

Surface soil aggregate velocity had a greater vertical component on the nose half than on the wing tip half of the wing surface. Such a difference implies a shearing action at the surface and a different manipulation by the nose than by the wing, possibly caused by the sweep nose or stem or the mounting shank directing soil flow upward.

Surface soil aggregates had approximately equal vertical and lateral movement while aggregates at the soil–tool interface had greater vertical movement. As sweep rake angle increased, soil aggregate flow paths at the soil–tool interface indicated a greater ratio of vertical to lateral movement. Greater vertical soil movement at the soil–tool interface and equal vertical and lateral movement at the soil surface implies twisting of the soil slice on the sweep.

For tillage with sweeps, surface soil velocities were generally unrelated to soil velocities on the tool surface. Such unrelated soil movements suggest random relative soil movement and a mixing action. Such mixing is beneficial for distributing plant nutrients, herbicide or weed seed at random depths within the tilled soil slice. This lack of correlation also suggests that a soil–tool model developed for a sweep should permit differences in soil movement within the soil slice. In particular, the model should permit different movement at the soil–tool interface and at the nose and wing sections on the soil surface.

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