PAPER NO. 82-1513

TILLAGE EQUATION FOR RESIDUE MANAGEMENT

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For presentation at the 1982 Winter Meeting
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

Palmer House, Chicago, Illinois
December 14-17, 1982

SUMMARY:
An equation which is easy to use on a small computer was derived to predict the effect of tillage on the removal of surface cover. The equation was checked using Iowa data for a chisel plow. More data is needed to fully verify the equation for other soil conditions and for tools other than a chisel plow.

1907-1982 75 ASAE Food, Fiber and the Future

American Society of Agricultural Engineers
St. Joseph, Michigan 49085

Introduction

Tillage tools are often analyzed in terms of forces on the tool rather than how the tool affects residue on the soil surface. Unfortunately soil erosion is highly dependent on the amount of residue cover remaining after tillage. While amounts of residue or fraction of soil cover before and after tillage operations have been measured (Colvin et al, 1980A; Dickerson et al., 1967; Greb et al., 1962; Sloneker et al., 1977; Woodruff et al., 1966) none of these researchers defined an equation to predict their measured results. While the development of such an equation may be a challenging endeavor, it is needed as one of the many components for better management of crop residue for soil conservation.

Development of General Equation

Tillage tools perform some or all of the following functions:

1. cut residue,
2. rake or divide residue,
3. move soil, and
4. mix residue in soil.

Residue can be in one of four forms or a combination of these forms:

1. unattached matured crop residue,
2. unattached green residue,
3. attached matured crop residue, and
4. attached green residue.

The nature of the residue (stems, leaves, stem diameter, etc.) varies with the crop and weeds on the field. Soil type, soil moisture, type of tillage tool, depth and speed of operation all affect the amount of soil moved, how the residue is divided and how the residue is mixed in the soil.

Some tillage tools such as planters and drills till only a strip with no change occurring to the untilled area. Other tools such as chisel plows and disks appear to till the complete area causing residue disturbance over the whole field.

A simple equation using dimensions given in Fig. 1 can be written to predict the new fraction of cover after tillage,

$$F_N = F_I \left(1 - \frac{W_D}{S} + \tau \frac{W_D}{S}\right) \qquad (1)$$

where

F_N = new fraction of cover,
F_I = initial fraction of cover,
W_D = width disturbed by individual tool (not to exceed S),
S = space between tools,
τ = a coefficient or function that varies with soil, residue and tillage tool variables. It is the fraction of the initial cover remaining on the disturbed strip after tillage.

If, for example, we were analyzing a 0.76 m (30 inch) row no-till planter in a field with an initial fraction of cover of 0.95 and W_D and τ were equal to 0.15 m and 0.5, respectively, then the calculation would be equal to .95 (1- .2 + .5(.2)), giving a new fraction of cover of 0.86. If we now adjusted the planter so that .38 m (15 in.) rows were obtained, the fraction of cover would drop to 0.76. If the same machine were run as a no-till drill with .25 m (10 in.) rows the fraction of cover would be 0.67. This illustrates the importance of row spacing and the amount of "within row" disturbance. If the row spacing becomes close enough so that W_D is equal to S then equation (1) reduces to

$$F_N = \tau F_I \qquad (2)$$

This is the form of equation that most researchers have used to evaluate their data. Colvin et al (1980B), for example, report τ values for different machines and residue types. We will develop a function for τ. We will use equation (1) as a general tillage equation.

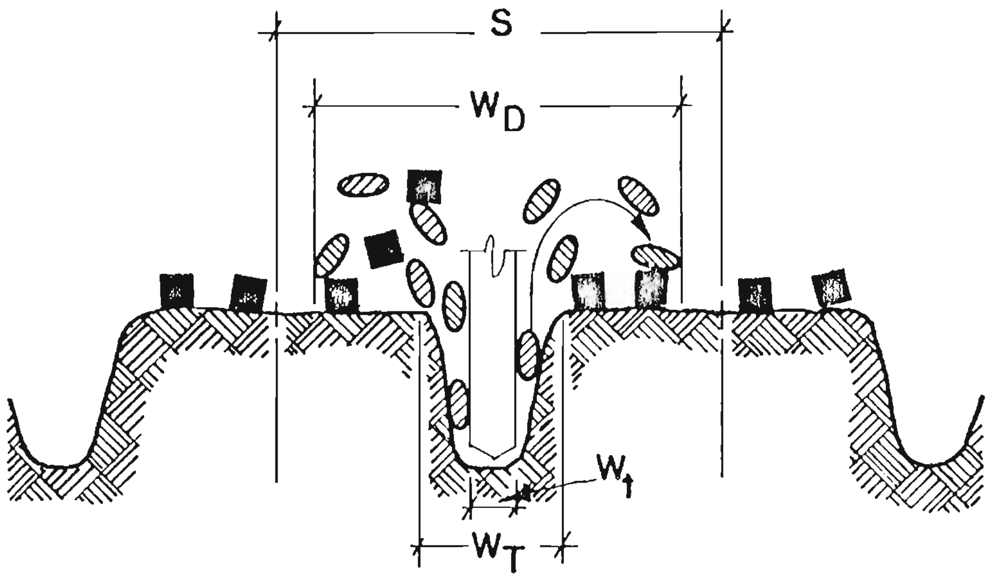

Fig. 1. Tillage machine operating in soil and residue.

Development of Function for τ

Since residue that is attached to the soil (e.g. growing plants or wheat stubble) will behave differently from residue that is cut and laying on the surface (soybean straw, wheat straw, or corn residue where stalks have been chopped), we will limit our development to one condition at a time. We will deal with the cut residue systems first.

Cut Residue System. A cut residue system is pictured in Fig. 2. In order for residue to be covered, soil must move up through the residue then fall back on the soil-residue surface covering both soil and residue. The amount of residue that gets covered depends on the amount of initial residue cover, the amount of soil that moves above the residue layer, and the form that the soil is in when it falls back to the surface. One large chunk of soil for example will not cover as much area as the same mass of soil broken into small particles.

The development will be in two parts: (1) the prediction of the mass of soil that moves above the residue, and (2) the prediction of the fraction of residue covered by this soil.

Part 1 - Prediction of Soil Movement Above Residue Layer

The mass of soil that moves above the pretilled soil surface will be defined as M_u. The total mass of soil moved by the tillage tool will be defined as M_t. The ratio M_u/M_t expresses the fraction of total soil tilled that moves above the initial soil surface. Not all of this soil, however, will move above the residue layer. If, for example, a particle of soil moves up under a piece of residue (See Fig. 2),

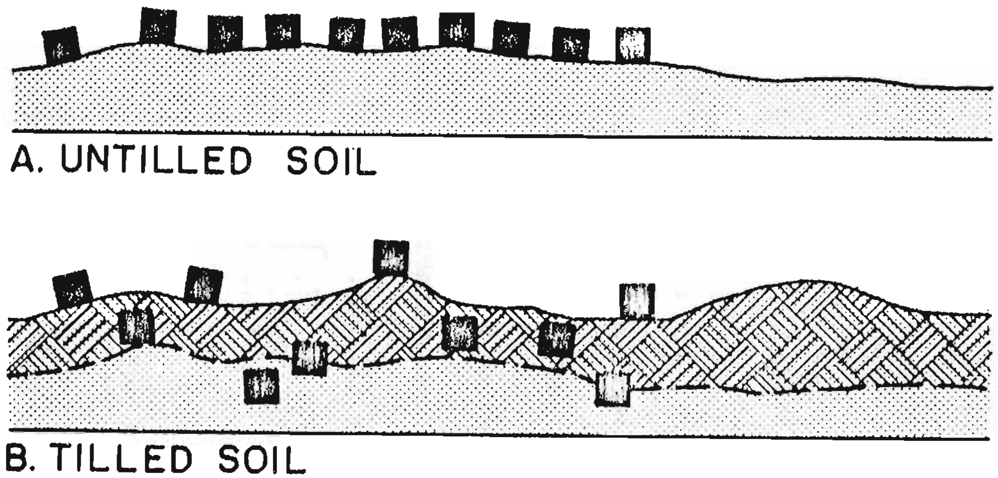

Fig. 2. A. Untilled soil with residue on the surface.

B. Tilled soil with cross-hatched area representing the fraction of tilled soil that moves above the pretilled soil surface.

the residue and the soil will be raised above the pretilled surface; but, the residue will not be covered by the soil. The probability of soil moving above the residue layer can be expressed as the fraction of soil that moves above the pretilled surface times the initial fraction of bare soil,

$$P = \left[1 - (F_S - F_S \frac{W_t}{W_T}) \right] \frac{M_u}{M_t} \qquad (3)$$

where

P = probability of soil moving above the residue layer,
F_S = fraction of stable residue cover (thin, partly decayed soybean leaves would not be considered as stable residue cover),
W_t = width of the individual tillage tool, such as fluted colter, and
W_T = width tilled or width affected by upward movement of soil.

Note that we have allowed for the tillage tool to divide and remove residue by allowing a decrease in the fraction of stable residue cover by the amount $F_S\ W_t/W_T$ due to the width of the tool.

The mass of soil which moves above the residue layer can be calculated by multiplying the probability P times the total mass of soil which is being moved by tillage,

$$M_S = \left[1 - F_S + F_S \frac{W_t}{W_T} \right] (\frac{M_u}{M_t})\ M_t \qquad (4)$$

where

M_S = mass of soil which moves above the residue layer, and
M_u/M_t = a fraction which is assumed to vary with soil moisture, soil type, speed and shape of tillage tool.

The total mass being tilled is equal to the bulk density times the average effective depth of tillage over the area disturbed times the area, so

$$M_S = \left[1 - F_S + F_S \frac{W_t}{W_T} \right] (\frac{M_u}{M_t})\ BD\ d\ A \qquad (5)$$

where

BD = bulk density before tillage,
d = average effective depth of tillage over area disturbed, and
A = area of tillage (area disturbed).

The average effective depth of tillage is defined here as the depth times the width of disturbance which will equal the same cross sectional area as that tilled.

The mass per area M_a is equal to M_S/A so

$$M_a = \left[1 - F_S + F_S \frac{W_t}{W_T} \right] \frac{M_u}{M_t} \ BD \ d \tag{6}$$

From equation (6), depth of tillage and two dimensionless parameters (W_t/W_T, M_u/M_t) appear to be important variables to predict the mass of soil per unit area that moves above the residue layer.

Part 2 - Prediction of residue covered by tilled soil

Gregory (1982) showed that the fraction of cover achieved from a mass of material randomly scattered over an area is given by

$$F = 1 - e^{-k \, M_a} \tag{7}$$

where

F = fraction covered,
k = a coefficient which has units of area/mass, and
M_a = mass of material expressed on a per area basis.

If M_a is the mass per area of soil which covers the soil-residue surface, then F is the fraction of the soil-residue surface covered by tilled soil. The reduction in residue cover due to the tilled soil falling on residue can now be expressed as the product of F and the initial fraction of cover in the disturbed zone as expressed with the following equation

$$R = F\, F_I \left(1 - \frac{W_t}{W_D}\right) \tag{8}$$

where

F_I = fraction of initial cover,
W_D = width disturbed by the tillage operation, and
W_T = the width of the individual tillage tool such as the width of the chisel tine.

The new fraction of residue cover F_t in this zone is equal to the initial cover minus the reduction in cover,

$$F_t = F_I \left(1 - \frac{W_t}{W_D}\right) - F\, F_I \left(1 - \frac{W_t}{W_D}\right) \tag{9}$$

The initial cover used in equations (8 and 9) is the cover after the tillage tool has passed by but before the soil has fallen back down. Equation (9) reduces to

$$F_T = F_I \left(1 - \frac{W_t}{W_D}\right) (1 - F) \tag{10}$$

Equation (7) can now be used to evaluate F in equation (10) to obtain

$$F_t = F_I \left(1 - \frac{W_t}{W_D}\right) (1 - (1 - e^{-k} M_a)) \tag{11}$$

Equation (11) can be simplified to

$$F_t = F_I \left(1 - \frac{W_t}{W_D}\right) e^{-k\, M_a} \tag{12}$$

The coefficient τ in equation (1) is the ratio of the new fraction of cover to the old fraction of cover so

$$\tau = \frac{F_I \left(1 - \frac{W_t}{W_D}\right) e^{-k\, M_a}}{F_I} \tag{13}$$

We can now use equation (6) to evaluate M_a to obtain

$$\tau = \left(1 - \frac{W_t}{W_D}\right) e^{-k(1 - F_S + F_S \frac{W_t}{W_T}) \frac{M_u}{M_t}\ BD\ d} \tag{14}$$

Obviously this equation is complex. It appears to offer no advantage over tables of measured coefficients. The equation, however, does suggest several variables that may be the key to a better understanding of the interaction of tillage and the residue-soil system. These variables are

1. $\frac{W_t}{W_D}$ ratio of tool width to width disturbed,
2. $\frac{W_t}{W_T}$ ratio of the tool width to width tilled,
3. $\frac{M_u}{M_t}$ ratio of mass of soil moved above untilled top of soil to total mass (M_t) moved by the tool,
4. d effective depth of tillage,
5. k clod size coefficient (area/mass), and
6. F_S fraction of stable residue cover.

The variables k, M_u/M_t, and BD are all soil related parameters. If we group the variables into one variable G, equation (14) reduces to

$$\tau = \left(1 - \frac{W_t}{W_D}\right) e^{-Gd\left(1-F_S + F_S \frac{W_t}{W_T}\right)} \qquad (15)$$

While this equation looks complicated, the variables may be easily defined for some machines. The variable F_S can be easily evaluated from residue mass using the fraction of cover equation developed by Gregory (1982). The variable W_t is the width of the tillage tool which can be measured directly. If the tillage units are close enough for the disturbance of one unit to overlap with the disturbance of the other, then W_D will be equal to the tool spacing. The furrow width will define W_T. The effective depth of tillage d can be computed from the tine depth and the variables W_t, W_T and W_D. The one variable that is difficult to obtain is G. While this variable is not easily measured, it may be relatively constant in the Midwest because much of the area is covered with silt loam topsoil.

Initial Verification of Equation (15)

To check equation (15), data reported by Colvin et al (1980 A) for a chisel plow operating in chopped corn residue and soybean residue were used. The corn data was used to determine values of the product Gd. These values were then used to predict fraction of cover left after tillage for soybeans.

Some information was needed to check the equation which was not reported. Tillage depth was not reported but based on a telephone conversation with Colvin in 1982, a tillage depth at the tine of 20 cm (8 in.) was assumed. Furrow width (W_T) at the ground surface was needed but this was not reported. We measured the furrow width on a straight shank 2 in. wide tine (same as Colvin's plow)and observed that the width was approximately equal to the depth of operation when the tine was operating at a depth of 15 cm (6 in.). Data from Schaaf et al (1980, Table 2, page 79) revealed that the ratio of furrow width to depth of tillage was approximately constant for a given tillage tool. Based on their data and our field measurement, we assumed a furrow width of 20 cm (8 in.) for Colvin's data. All of the cover associated with the corn residue was assumed to be stable. From experiments with soybean residue we have found that about 30 percent of high yielding (2700 kg/ha or 40 bu/ac +) soybean residue is in the form of leaves and pod hulls. We assumed that the pod hulls were stable but that the leaves were fragile and would be destroyed by tillage. Of the 30%, we assumed that one half were leaves giving a stable residue mass for soybean residue of 85 percent. The fraction of stable residue cover for soybeans was then estimated using soybean stems and Fig. 4 of Gregory (1982).

The measured values and predictions are given in Table 1. Using a Gd value based on average τ values for corn gave very good predictions of τ values for soybeans. At site 1 the predicted value was within 5 percent of the measured value and at site 2 the error was 10 percent. While several assumptions were made to check equation (15), it is believed that they are reasonable. It was concluded at this point that equation (15) is an acceptable function to predict the effect of tillage for the condition of unattached residue.

Equation (15) was then used to show the effect of initial cover on the value of τ for corn in Fig. 3 and soybeans in Fig. 4. The range of Gd values obtained in Table 1 was also used to give some indication of the range of variation that might be expected for τ due to soil conditions.

Attached Residue System. The attached residue system will behave differently from the cut residue system because the soil attached to the residue does not have the freedom to move without also moving the residue. The attached residue will also probably be partially standing and thus may not be covering the soil at full potential for the given residue mass. An attached residue system with some cut residue is shown in Fig. 5.

During a tillage operation the cut residue should behave as described by equation (15). The attached residue, however, will move along with the soil. The attached residue, for example a wheat stubble, can be observed to occur in bundles of residue all attached to a soil clod. This bundle will cover the surface partly with residue and partly with the soil. If there were sufficient number of bundles to completely cover the surface then the final fraction of cover would equal the ratio of residue area to the

Table 1 Measured data[1] and Predictions using Equation (15)

Corn			Soybeans		
Site 1	F_I = 0.96		Site 1	F_I = 0.61	
	W_D = 30 cm			W_D = 30 cm	
Ames Iowa	W_t = 5 cm		Ames Iowa	W_t = 5 cm	Predicted
	F_N = 0.42	Gd = 2.30		F_N = 0.15	. . . . F_N = 0.16
	τ = 0.438			τ = 0.25	. . . . τ = 0.26
	W_T = 20 cm*			W_T = 20 cm*	
	F_S = F_I			F_S = 0.22*	
Site 2	F_I = 0.95		Site 2	F_I = 0.83	
	W_D = 30 cm			W_D = 30 cm	
Castana Iowa	F_S = F_I		Castana Iowa	W_t = 5 cm	Predicted
	W_t = 5 cm	Gd = 0.687		F_N = 0.26	. . . . F_N = 0.28
	F_N = 0.65			τ = 0.31	. . . . τ = .34
	τ = 0.684			W_T = 20 cm*	
	W_T = 20 cm*			F_S = 0.38*	
Average	F_I = 0.955				
	W_D = 30 cm				
	F_S = F_I	Gd = 1.39			
	W_t = 5 cm				
	τ = 0.561				
	W_T = 20 cm*				

*Estimated values as discussed in text

1 Measured data from Colvin, et al. (1980 A)

Average F_N = 1.8

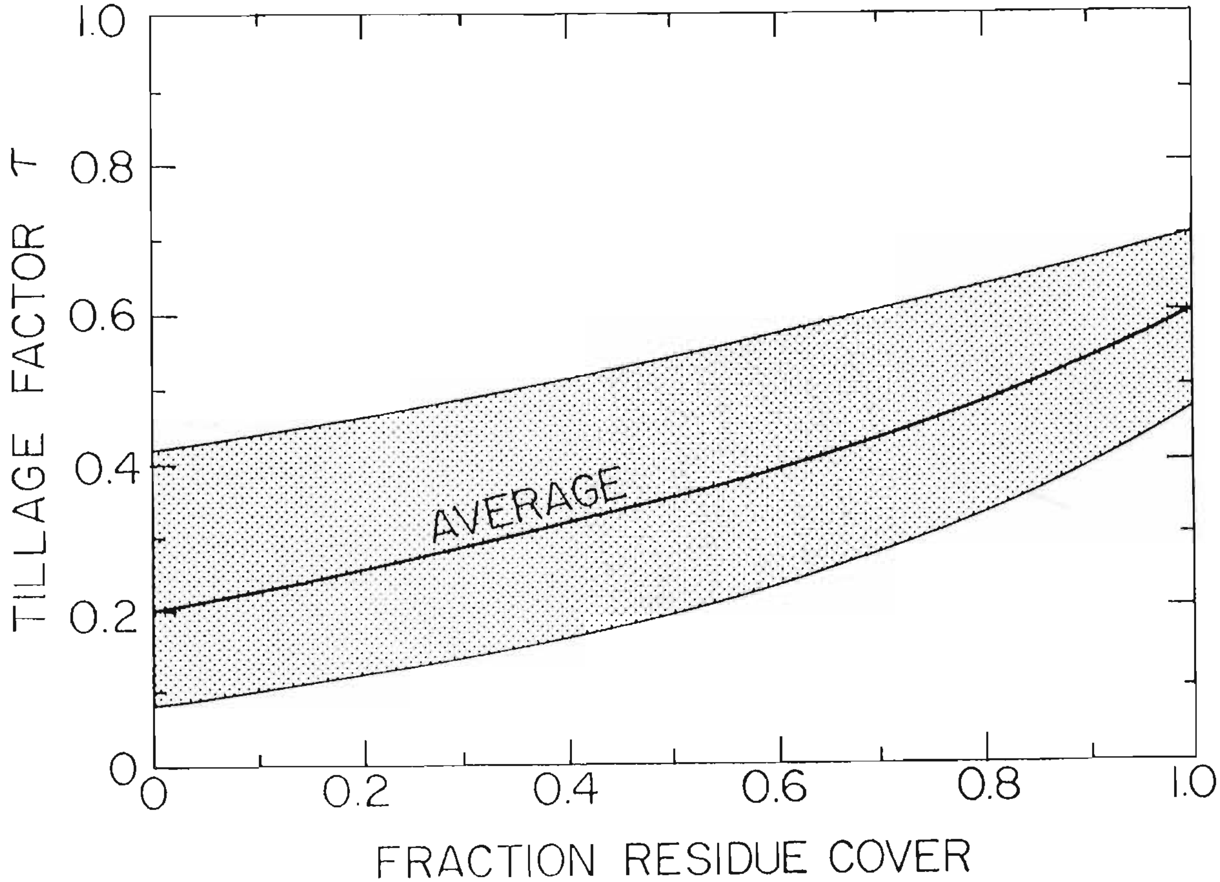

Fig. 3. Tillage factor τ for a chisel plow operating in corn residue. Values were calculated with equation (15). Equation (15) was calibrated with measured data reported by Colvin et al (1980A).

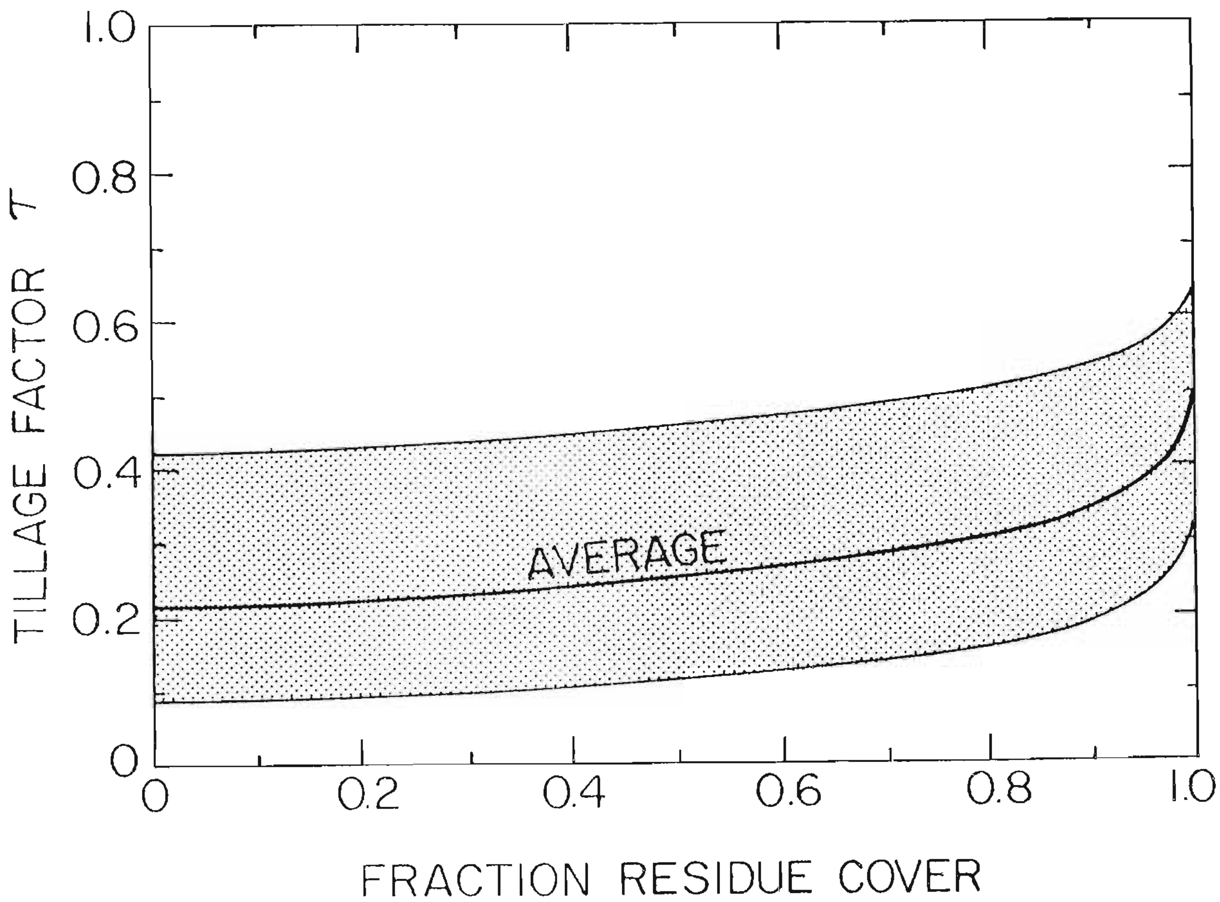

Fig. 4. Tillage factor τ for a chisel plow operating in soybeans. Predictions were made with equation (15) and calibrated using corn data from Colvin et al (1980A).

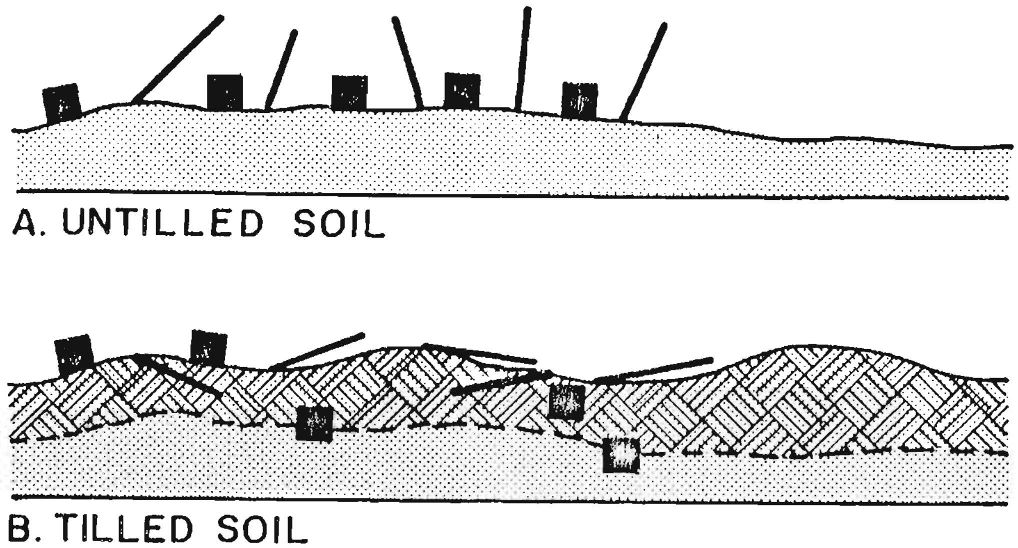

Fig. 5. A. Untilled soil with unattached and attached crop residue on surface.

B. Tilled soil with cross-hatched area representing the fraction of tilled soil that moves above the pretilled soil surface. Note also that attached residue remaining on the surface covers more area than it did before tillage.

total area of residue plus area of the clod cross section. The fraction of cover given by the residue portion of the bundles can be evaluated using equation (7). Since for every unit of residue area we add to the system, we also add a fraction of a unit of soil area, the final fraction of cover given by the bundles can be computed by multiplying the fraction of cover obtained from the residue portion of the bundles by the ratio of residue area over total area of residue and soil,

$$F_A = \frac{A_r}{A_s + A_r} (1-e^{-K M_r}) \tag{16}$$

where

F_A = fraction of residue cover after tillage from attached residue before tillage,
A_r = area of residue,
A_s = cross section area of clod,
K = a coefficient for a given type of residue (see Gregory [1982] for values), and
M_r = mass of material (attached residue).

The fraction of cover from attached residue F_A will cover some bare soil and some cut residue that did not get covered by the tillage operation. The total cover is computed by multiplying the fraction of bare soil from both types of residue and subtracting this value from one;

$$F_f = 1 - (1 - F_A)(1 - F_t) \tag{17}$$

where

F_f = the final fraction of cover,
F_A = the value from equation (16, and
F_t = the value from equation (12).

Equation (17) can be simplified to

$$F_f = F_A + F_t - F_A F_t \tag{18}$$

If equation (18) is divided by the initial fraction of cover F_I then τ in equation (1) is obtained. Thus a general tillage equation can be written as follows:

$$F_N = F_I \left[1 - \frac{W_D}{S} + \frac{W_D}{S} \left(\frac{F_A}{F_I} + \frac{F_t}{F_I} - \frac{F_A F_t}{F_I}\right)\right] \qquad (19)$$

where $F_A = \left(\frac{A_r}{A_s + A_r}\right) \quad (1-e^{-K\ M_r})$, and

$$F_t = F_I \left(1 - \frac{W_t}{W_D}\right) \quad e^{-Gd} \left(1 - F_s + F_s \ \frac{W_t}{W_T}\right)$$

Example Problem

Colvin et al, (1980 A) reported data for fall chisel plow after corn harvest. No indication of chopping stalks was given. They measured an initial fraction of cover of 0.98 and a cover after tillage of 0.84. We will attempt to work this problem with equation (19).

First according to Gregory's work (1982) a cover fraction of .98 would require a corn yield of about 9700 kg/ha (155 bu/ac). We will assume that one-half of the residue is still attached and that the other residue behaves as cut residue. If one-half of this residue were cut and spread out on the field, a cover of .86 should occur. Next we will assume that the attached residue is in the form of stalks 61 cm (2 ft.) long, 2.5 cm (1 in.) wide, and after tillage will have a soil clod attached with a diameter 7.6 cm (3 in.). The ratio of residue area over total area of residue and soil is 0.77. This value times the 0.86 for cover for one-half of the total residue mass gives a value of 0.66 for F_A. Using a chisel plow of the same dimensions as described in Table 1 and a residue cover on the soil surface of 0.86, a value of 0.44 is obtained for F_t. When these values are substituted into equation (19) a value of 0.81 is obtained for F_N. Note that W_D/S for this problem is 1.0. Considering all of the assumptions that were made, the prediction of 0.81 is quite close to the measured value of 0.84. More importantly, the problem illustrates the importance of considering attached residue separate from cut residue. Had we assumed all of the residue was cut and made the calculation for an initial cover of 0.98, the new cover would have been only 0.56. From a management point of view for erosion control, a farmer would be better off to chisel plow without cutting stalks than cutting stalks and then chisel plowing.

Conclusions

An equation has been derived to predict the effect of tillage on the removal of surface cover. The equation was initially checked with data collected in Iowa. More data is needed to fully verify the equation for other soil conditions and for tools other than a chisel plow. The equation appears to be complex but certainly not difficult to use on a small computer.

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