STUDY OF TILLAGE TOOL–SOIL–CROP RESIDUE INTERACTION

BY

JUDE LIU

A Thesis Submitted to the Faculty of Graduate Studies in Partial
Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

Department of Biosystems Engineering

University of Manitoba
Winnipeg, Manitoba

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

COPYRIGHT PERMISSION

Study of Tillage Tool-Soil-Crop Residue Interaction

BY

Jude Liu

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

Of

DOCTOR OF PHILOSOPHY

ACKNOWLEDGEMENTS

The work for this thesis was carried out in the Department of Biosystems Engineering, University of Manitoba.

I am grateful for my advisors Dr. Ying Chen and Dr. David A. Lobb for their invaluable support. I wish to express my gratitude to my committee members, Dr. Neil McLaughlin, Dr. R. L. Kushwaha, Dr. Danny Mann and Dr. James Blatz for their invaluable suggestions.

I want to thank Mr. Alvin Iverson, the manager of Carman Research Station in Manitoba, for supporting my field experiment. I specially thank technicians: Mr. Dale Bourns, Gerry Woods, Matt MacDonald, and Derek Inglis in the Department of Biosystems Engineering for giving me great help in my experiments.

I am very grateful for the love and support of my wife Zhifang Chen and son Qiang Liu. They provided me great help during my study.

This work was financially supported by the Graduate Fellowship of the University of Manitoba and NSERC.

ABSTRACT

Soil and surface straw movement by a single sweep tool were experimentally studied, and then physically based mathematical models were developed and validated. Soil bin and field experiments were conducted using cereal straw and a 325-mm-wide sweep to study soil and straw interaction. Experimental factors were tillage speed and straw length. Results indicated that higher tillage speed resulted in larger soil and straw displacement and more straw being buried; there was less longer straw buried than shorter straw at the same tillage speed. The results of the soil bin experiment showed that the forward soil displacement would be reduced by at least 70% if tillage speed was reduced from 10 km/h to 5 km/h regardless of straw length.

The soil-moving zone in front of a single sweep was studied, and a steady-state model was proposed to calculate the quantities of soil and straw in the moving zone. Two additional steady-state models were developed based on existing soil failure models. These models were validated by the soil bin experiment. A soil displacement model was then developed and validated with the data obtained from the above soil bin and field experiments. The relative error of the soil displacement model was less than 19%. According to the soil displacement model, straw displacement was also modeled, and its the accuracy was between 73% and 93% depending on the length of straw. The parameters involved in both soil and straw displacement models were soil properties, tool geometric parameters, tillage speed, and tillage depth. Straw length was also included in

the straw displacement model. Finally, soil and straw redistribution after tillage with a single sweep was modeled based on the soil and straw displacement models. The redistribution model fitted well with the results of the soil bin experiment. It could be concluded that the models developed above would predict the soil and straw interaction during tillage with a single sweep. It should be noted that the validating tests were conducted only at a constant tillage depth under the same soil conditions.

This dissertation was written in a paper format. Part of content in chapters may be duplicated.

TABLE OF CONTENTS

Page

ACKNOWLEDGMENT

ABSTRACT

LIST OF FIGURES

CHAPTER 2

CHAPTER 3

Figure 4. Assumptions of the soil moving zone in front of a sweep

CHAPTER 4

CHAPTER 5

LIST OF TABLES

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 1

Introduction to the Study of Tillage Tool–Soil–Crop Residue Interaction

1 RESEARCH BACKGROUND

Tillage has been and will always be integral to crop production, and plays an important role. Tillage includes all field operations that are designed to lift, invert, stir, and pack soil, reduce the size of clods and uproot weeds. Soil and crop residues whereby are disturbed and relocated by soil engaging tools; that is, tillage practices are always accompanied by soil and crop residue movement.

The high intensity of soil translocation has been detected and recognized as a main mechanism of soil degradation on cultivated fields (Lindstrom et al., 1992) in 1990's, though soil translocation had been studied decades earlier (Mech and Free, 1942). Tillage operations also significantly affect crop residue cover, which protects soil from erosion caused by water and wind (Doughty et al., 1949). However, knowledge of understanding the interactions of tillage tool, soil, and crop residue is still not available. The research of tool–soil–crop residue interaction has progressed slowly due to its complexity: tillage equipment mechanically moves soil; the soil movement affects the movement and incorporation of crop residue; and crop residue in turn affects soil movement. Moreover, soil movement is necessary in terms of residue burial; but unnecessary as soil and residue movement introduces the high consumption of energy and possible soil erosion.

To understand the interactions of tool, soil and crop residue, the processes of the interactions must be quantified and represented in the form of conceptual and mathematical models. Such models could be used to simulate the soil and crop residue movement and crop residue incorporation for existing tools; or to forecast and optimize soil conservation and energy requirements while designing a new tool. However, these models are not currently available. This study was carried out in this background.

2 LITERATURE REVIEW

2.1 Soil and Straw Movement

Researchers (e. g. McKyes, 1985; Kouwenhoven and Terpstra, 1973) realized that the shape, width and rake angle of an individual tool strongly influences soil movement. Forward and lateral movement of soil (throwing of soil to the sides of a tool) tends to increase when increasing the width of an implement. Study of soil movement is primarily involved in two research areas, soil erosion and soil–machine systems. Generally speaking, the study of soil erosion deals with two basic questions: how much soil is moving and how far it moves. To answer these questions, researchers defined linear or non-linear equations for soil movement (Lobb and Kachanoski, 1999). Govers et al. (1994) proposed a diffusion equation of soil flux, which is the product of a diffusion coefficient and the slope gradient. The amount of moving soil and translocation could be calculated by the experimental diffusion curve obtained with a tracer method. However, this equation could not describe soil particle displacement and soil distribution by tillage tool. Other similar models can be found in some publications (e.g. Lindstrom et al., 2000; Poesen et al., 1997; De Alba, 2001). Whatever the formats of these models are, they are stochastic representations of one-dimensional soil movement rather than physically based equations. The effect of tillage depth and speed are implicitly represented. Large amount of field measurements is required to determine those parameters in a model.

Lobb et al. (1995) proposed that the soil displacement during tillage consists of primary displacement, projection, and sliding and rolling. These movement phases could be separately measured with the experimental methods; but, no physically based equations were proposed. According to this concept, Torri and Borselli (2002) simplified soil movement as a three-phase motion: drag, jump, and rolling. Each phase depends on measurable characteristics of tillage tools and the soil. Under the assumptions of clod ejecting and rolling, equations of soil displacement were derived and then tested by a clod launcher experiment. Little information is available on integrating soil movement with crop residue incorporation. In addition, how to calculate soil displacement specially the projectile displacement is not mathematically presented. Sharifat (1999) developed a soil movement model according to the stress distribution of soil in front of a tillage tool. The influences of soil parameters were treated as independent variables, and they were involved into the model through regression analysis. Rahman (2004) studied soil movement in a soil bin using point tracers, but only regression relations were proposed. None of these models clearly presented the amount of moving soil. No literature was found on studying the movement of crop residues during tillage.

In the area of soil–machine systems, tillage and soil cutting have been studied, and soil-cutting models were well developed through studying the pattern of soil failure in front of a tool. These research achievements from 1912 to 1965 were well documented by Gill and Berg (1968). Other publications (e.g. Koolen and Kuipers, 1983; McKyes, 1985) described updated research achievements. The patterns of soil failure in these studies include two-dimensional and three-dimensional models, which were based on the assumptions that the interaction between soil and tool is static; the process of soil cutting is a repeated failure by shearing. Soil failure forms small soil blocks on the surface of a tool.

Three-dimensional soil-cutting models were originally proposed for a cutting blade (e.g. Hettiaratchi and Reece, 1967; McKyes and Ali, 1977; Godwin and Spoor, 1977; Grisso et al., 1980). The basic concept of these models was that there is a limited area in front of a tool, where soil fails. The limited area consists of three zones: one essential zone and two side zones. Each model defined a distinguished geometry of failure zone. It is believed that the soil mass in the failure zone is an instant quantity of soil being moved by the tool during tillage. Thus, these models could be used to estimate the amount of soil moving, although they could not describe the distance of soil moving and soil redistribution by tillage.

A gap was found between those two research areas mentioned above. On one hand, the current methods of estimating the amount of moving soil was developed in the study of soil erosion. They are based on experiments, but not physically related to the type of tillage tool and tillage operating parameters. On the other hand, soil-cutting models described the mechanics and geometry of soil failure in front of a tool, but they have not been used in the study of soil erosion. Moreover, the models of soil displacement and crop residue incorporation were not developed in both areas. A study is apparently required to close this gap.

2.2 Straw Incorporation

Tillage operation impacts crop residue cover, which protects soil from erosion caused by water and wind (Doughty et al., 1949). Increasing residue cover, even by a small amount, decreases soil erosion potential (Laflen and Colvin, 1981). Since high amount of residue are not needed and could make tillage and seeding operations difficult, part of the crop residue needs to be incorporated into soil (Chen et al., 2004). Therefore, knowledge of crop residue incorporation is required, such as the ability of tools to break down, spread, and incorporate residue; the suitability of tools and their arrangement to deal with mechanical problems (e.g. wrapping and clogging) which could adversely affect equipment performance, and the quantity of the residue produced by a crop. Simply speaking, this knowledge should help to choose the appropriate tillage implements to handle crop residues for efficient crop production and optimum erosion control.

Effect of tillage on residue cover depends on speed, depth of operation, type of implement, and soil conditions, plus the type and height of residue (Woodruff and Chepil, 1958). However, information on implement configuration, and operating depth and speed has usually been omitted as described by Hanna et al. (1995). Research of crop residue incorporation by tillage primarily includes two aspects. One is the effect of tillage on crop residue cover to answer how much crop residue is needed for protecting soil from erosion; the other is to establish a relationship between tillage implement and crop residue coverage. The residue cover needed to effectively control erosion is controversial though it is defined as minimum 30% after seeding in conservation tillage (Jasa, 2002). All studies of the second aspect were done by empirical methods based on field experimental data (e.g. Gregory, 1982; Wagner and Nelson, 1995).

The research of crop residue incorporation has progressed slowly since there are many factors affecting residue incorporation. Knowledge of understanding the process of soil and crop residue interaction during tillage is not currently available. Therefore, study of tillage tool–soil–crop residue interaction is needed.

Researchers have studied for ages to establish relationships between tillage implements and crop residue cover. Gregory et al. (1982) attempted to quantify the effect of tillage on the crop residue after harvest by deriving a tillage equation that includes the initial fraction of surface cover, tillage tool dimensions, and soil and operational parameters. This equation is valid for data from the experiment with a chisel plow. Tillage depth and soil clay content were eventually added in this equation by Koohestani and Gregory (1985). To quantify this equation, following data has to be measured: the width of soil disturbance, the width tilled or affected by upward movement of soil, the depth of tillage at the chisel point, the area covered by soil, and the mass of soil that moved above the untilled soil surface. Koohestani and Gregory (1985) realized the complexity of this equation that requires many field measurements. However, it provides a better understanding of the interactions between tillage tool, soil, and crop residue. Tillage translocation was not considered. All studies mentioned above were conducted by empirical methods based on measurements on specific fields.

2.3 Soil Disturbance

Soil disturbance associated with tillage operation has been studied (Owen, 1988). McKyes (1985) described results of soil disturbance, and indicated that the shape, width and rake angle of tools strongly influence the transport and mixing of soil particles; the throwing of soil to the sides of a tool rises also with the square of tillage speed. Dowell et al. (1988) found that the ridge height and lateral distance of soil by a sweep increased with tillage speed. Hanna et al. (1993) concluded that sweeps with larger rake angle working at higher tillage speed resulted in more movement of soil and built higher ridges in a study of changes in soil microtopography by tillage. Sharifat and Kushwaha (1999) studied soil profile after tillage with a single tool, and proposed a soil lateral displacement index. It was found that soil profile for a sweep tool was as a triangle, and a parabolic for a furrow opener. However, all these studies were carried out based on a field or soil bin experiment. Measurements included the width and the section area of soil disturbance as well as soil bulk density before and after tillage operation. No mathematical models were developed based on the physical process of soil and straw interaction. Three-dimensional soil failure models could be used to estimate the cross-section of the soil disturbance, but the soil thrown to the sides of a tool was not considered in these models. Hence, it is necessary to study and model soil and straw redistribution by tillage.

2.4 Experimental Methods

Experimental methods were surveyed to obtain appropriate data. It would be too hard to control parameters and clearly explain the interaction of tillage tool–soil–crop residue in a fieldwork. Indoor soil bin test facilities have many advantages over field tests in studying tool and soil interaction, such as easily controlled soil conditions. Hence, soil bin has been used to acquire data that helps to understand the process of tool, soil, and crop residue interactions. Kushwaha et al. (1986) studied straw cutting ability of powered-disc coulters in a soil bin. No other literature was found regarding studies of soil and crop residue interaction in a soil bin. However, a field experiment is also needed to examine the differences between soil bin and field experiments depending on the purposes of a study. In addition, no literature was found that studies straw movement in either a soil bin or a field. Therefore, it is necessary to study experimental methods of conducting this research in a soil bin for the purpose of long-term research.

Methods for measuring soil movement were developed in the study of tillage translocation, which can be categorized into direct and indirect methods. Indirect methods are used to determine soil translocation by measuring soil diffusion curve using tracer methods, and the amount and distance of relocated soil are calculated by the diffusion curve. Tracers are classified as bulk tracers and point tracers. Point tracers are individually labeled objects of various shapes and materials, e.g. steel nuts (Lindstrom et al., 1992), plastic spheres (Govers et al., 1994), and cubes (e.g. Rahman, 2004). Bulk tracers are used to label a volume of soil; they can be physical, e.g. gravel (Turkelboom, et al., 1999), or chemical, e.g. Cl (Lobb, et al., 1995). Point tracers also represent a volume of soil, and they have the distinct advantage that they can be used to characterize the complexity of soil movement in three dimensions. Hence, point tracer was selected as a mean for measuring soil and straw displacement.

Direct methods are mainly used to measure the amount of soil being relocated by tillage. The basic concept of direct methods is to create a space in another media that allows soil to be moved in by tillage, and then to measure the mass of the soil moved in. Mech and Free (1942) dug a hole in a soil box and filled it with gravel. The quantity of soil moved in the gravel was measured by separating soil and gravel after tillage. Turkelboom et al. (1999) also suggested an open hole to calculate soil translocation. The open hole had a trapezoid section profile, which should be filled full after tillage operation. The soil translocation was then measured.

Although there have been studies of soil movement and residue incorporation by tillage in the Canadian prairie and elsewhere in the world, there have been no studies which examine both soil and crop residue movement and their interaction. Besides, no studies examined crop residue incorporation and its relationships to soil and crop residue movement. The goal of this study was to provide design and research basis for assessing the performance of tillage tools aimed at effectively managing crop residue for soil conservation and efficient crop production. In this study, cereal straw was used as the crop residue, and the tillage tool was a sweep because cereal crop is popular and sweep is one of common tillage tools in this region.

3 OBJECTIVES

3.1 To Experimentally Study the Interactions of Tillage Tool, Soil and Straw

a) To compare the experimental methods of measuring soil and straw movement in a soil bin;

b) To study effect of straw length and tillage speed on soil and straw movement, and straw burial; and

c) To compare the results of a soil bin experiment with a field experiment.

3.2 To Develop Steady-State Models of Soil and Straw Moving during Tillage

a) To apply two existing soil-cutting models, McKyes and Ali's model and a two-dimensional model, to the study of the amount of soil and straw moving by a sweep;

b) To develop a new mathematical model for predicting the amount of soil and straw moving by a sweep; and

c) To validate these models with a soil bin experiment.

3.3 To Develop a Model of Soil Movement by Tillage

a) To develop a mathematical model to describe the soil displacement by a single sweep based on the physical process of soil and tool interaction;

b) To incorporate the effect of crop residue on soil movement into the soil displacement model; and

c) To validate the model by a soil bin and a field experiments.

3.4 To Model Straw Incorporation by Tillage

a) To develop a mathematical model of straw displacement for a single sweep;

b) To develop a mathematical model of soil and straw redistribution after the tillage with a single sweep; and

c) To validate these models with a soil bin experiment.

4 REFERENCES

Chen, Y., F. Monero, D. Lobb, S. Tessier and C. Cavers. 2004. Effects of six tillage methods on residue incorporation and crop performance under a heavy clay soil condition. *Transactions of ASAE.* In press.

De Alba, S. 2001. Modeling the effects of complex topography and patterns of tillage on soil translocation by tillage with mouldboard plough. *Journal of Soil and Water Conservation.* 56(4): 335-345.

Doughty, J. L., W. J. Staple, J. J. Lehane, F. G. Warder, and F. Bisal. 1949. Soil moisture, wind erosion and fertility of some Canadian prairie soils. Department of Agriculture, Canada. Publication 819, Technical Bulletin 71.

Dowell, F. E., J. C. Siemens and L. E. Bode. 1988. Cultivator speed spacing effects on herbicide incorporation. *Transactions of ASAE* 31(5): 1315-1321.

Gill, W. R. and G. E. V. Berg, 1968. *Soil dynamics in tillage and traction.* Agriculture Research Service. Washington D. C., Department of Agriculture, US.

Godwin, R.J and G. Spoor. 1977. Soil failure with narrow tines. *Journal of Agricultural Engineering Research*, 22: 213-228.

Govers, G., K. Vandaele, P. J. J. Desmet, J. Poesen, and K. Bunte. 1994. The role of tillage in soil redistribution on hillslopes. *European Journal of Soil Science* 45: 469-478.

Gregory, J. M. 1982. Soil cover prediction with various amounts and types of crop residue. *Transactions of ASAE* 25(5): 1333-1337.

Gregory, J. M., T. M. McCarty, F. Ghidey, and D. L. Pfost. 1982. Tillage equation for residue management. ASAE paper No.82-1513, St. Joseph, MI.

Grisso, R. D., J. V. Permpral, and C. S. Desai. 1980. A soil-tool interaction model for narrow tillage tools. ASAE Paper 80-1518 St. Joseph, MI.

Hanna, H. M., D. C. Erbach, S. J. Marley, and S. W, Melnin. 1993. Changes in soil microtopography by tillage with a sweep. *Transactions of ASAE* 36(2): 301-307.

Hanna, H. M., S. W. Melvin, and R.O. Pope. 1995. Tillage implement operational effects on residue cover. *Applied Engineering in Agriculture*. 11(2): 205-210.

Hettiaratchi, D. R. P. and A. R. Reece. 1967. Symmetric three-dimensional soil failure. *Journal of Terramechanics*, 4(3): 45-67.

Jasa, P. J. 2002. Conservation tillage systems. www.agecon.okstate.edu/isct/labranza/jasa/tillagesys.doc, Accessed: Feb. 04, 2002.

Koohestani, M. and J. M. Gregory. 1985. Measurement of tillage parameters that affect residue cover. ASAE paper No. 85-2045, St. Joseph, MI.

Koolen, A. J., and H. Kuipers. 1983. *Agricultural Soil Mechanics*. New York, N. Y.: Springer-Verlag.

Kouwenhoven, J. K. and R. Terpstra. 1973. Mixing of glass spheres by tines. *Journal of Agricultural Engineering Research*, V.18: 321-332.

Kushwaha, R. L., A. S. Valshnav, and G. C. Zoerb. 1986. Performance of powered-disc under no-till crop residue in the soil bin. *Canadian Agricultural Engineering*, 28(2): 85-90.

Laflen, J. M. and T. S. Colvin. 1981. Effect of crop residue on soil loss from continuous row cropping. *Transactions of ASAE* 24(3): 605-609.

Lindstrom, M. J.; W.W. Nelson, and T. E. Schumacher. 1992. Quantifying tillage erosion rates due to moldboard plowing. *Soil & Tillage Research, 24*, 243-255.

Lindstrom, M. J., J. A. Schumacher, and T. E. Schumacher. 2000. TEP: a tillage erosion prediction model to calculate soil translocation rates from tillage. *Journal of Soil and Water Conservation*. 55(1): 105-108.

Lobb, D. A., R. G. Kachanoski, and M. H. Miller. 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using Cs-137 as a tracer. *Canadian Journal of Soil Science*. 75:211-218.

Lobb, D. A. and R. G. Kachanoski. 1999. Modeling tillage translocation using step, linear-plateau, and exponential functions. *Soil & Tillage Research*. 51: 261-277.

Lobb, D. A. and E. Huffman. 2004. Importance of information on tillage practices in the modeling of environmental processes and in the use of environmental indicators. OECD Expert Meeting on Farm Management Indicators and the Environment. Palmerston North, New Zealand, March 8-12, 2004.

McKyes, E. 1985. *Soil Cutting and Tillage*. Elsevier Science Publishing Company Inc. 52 Vanderbilt Avenue, New York, NY10017, U.S.A

McKyes, E. and O. S. Ali. 1977. The cutting of soil by narrow blades. *Journal of Terramechanics*. 14(2): 43-58.

Mech, S. J. and G. R. Free. 1942. Movement of soil during tillage operation. *Agricultural Engineering*. 23(12): 379-382.

Owen, G. T. 1988. Soil disturbance associated with deep subsoiling in compact soils. *Canadian Agricultural Engineering*, 30(1): 33-37.

Poesen, J., B. van Wesemael, G. Govers, J. Matinez-Fernadez, P. Desmet, K. Vandaele, T. Quine, and G. Degraer. 1997. Patterns of rock fragment cover generated by tillage erosion. *Geomorphology* 18:183-197.

Rahman, S. 2004. Soil movement and manure placement from liquid manure injection tool. Unpublished Ph.D. thesis. Winnipeg, MB: Department of Biosystems Engineering, University of Manitoba.

Sharifat, K. 1999. *Soil translocation with tillage tools*. Unpublished Ph.D. thesis. Saskatoon, SK: Department of Agricultural and Bioresource Engineering, University of Saskatchewan.

Sharifat K. and R. L. Kushwaha. 1999. Lateral soil movement by tillage tools. ASAE Paper No.991003. St. Joseph, Mich.: ASAE.

Torri, D. and L. Borselli. 2002. Clod movement and tillage tool characteristics for modeling tillage erosion. *Journal of Soil and Water Conservation*. 57(1): 24-28.

Turkelboom, F., J. Poesen, I. Ohler, and S. Ongprasert. 1999. Reassessment of tillage erosion rates by manual tillage on step slopes in northern Thailand. *Soil and Tillage Research*. 51(3-4): 245-259.

Wagner, L. E. and R. G. Nelson. 1995. Mass reduction of standing and flat crop residues by selected tillage implements. *Transactions of the ASAE*. 38(2): 419-427.

Woodruff, N. P. and W. S. Chepil. 1958. Influence of one-way-disk and surface-sweep tillage on factors affecting wind erosion. *Transactions of ASAE* 1:81-85.

CHAPTER 2

Experimental Study of Tillage Tool–Soil–Straw Interaction

ABSTRACT

Three experiments were conducted in a soil bin and a field to study soil and straw movement and straw incorporation by tillage. The soils in the bin and the field had the same texture of loamy sand. Cereal straw was selected as a crop residue. The length of straw ranged from 50 to 250 mm with increment of 25 mm. Tillage tool was a 325-mm-wide sweep, and it was operated at the speeds of 5, 7.5, and 10 km/h with constant depth of 100 mm. Point tracers were used to measure soil and straw displacement. Results showed that longer straw were less buried than shorter straw at the same tillage speed. Higher tillage speed resulted in larger soil displacement that also buried more straw. Straw displacement increased with increasing straw length. Straw displacements measured with two different orientations of straw tracers were not significantly different. The straw mixture of different lengths worked well in studying straw movement and incorporation. The results of the soil bin experiment indicated that the forward soil displacement was reduced by 70% and greater if tillage speed was reduced from 10 km/h to 5 km/h independent of the straw length. Soil rolling in the field was greater than in the soil bin when there was no stubble in the field. Standing stubble significantly reduced soil displacement by resisting soil rolling. The straw cover measured from the field and the soil bin were not statistically different for 100 and 175-mm-long straw. Studying straw incorporation in a soil bin would not have significant differences with doing it in a field under the same soil moisture content and bulk density if straw was shorter than 250 mm.

1 INTRODUCTION

Study of tillage tool–soil–crop residue interaction is important due to it is involved in several central research topics in crop production, such as soil erosion and crop residue incorporation. The final distribution of soil and crop residue was determined by both soil and crop residue movement, and this movement caused by tillage implement. Therefore, understanding the relationship between soil, crop residue and tillage tool is important.

The effect of tillage on residue cover depends on the speed and depth of tillage operation, type of implement, soil conditions, and the type and height of residue (e.g. Woodruff and Chepil, 1958; Chen et al., 2004). Hanna et al. (1995) studied the effect of operational factors on residue cover using a disk, a chisel, and a knife opener. They reported that shallower tillage depth and slower speed could reduce residue burial. Woodruff et al. (1965) studied the effect of standing residue on total surface residue after tillage; but soil and straw movement affected by standing residue was not included. Previous studies on crop residue management were based on field measurements. These data could not be used for interpreting the physical process of soil, tillage tool, and crop residue interactions. In addition, soil movement affecting straw movement and incorporation was not considered.

Other research areas that deal with soil and tillage tool interaction are soil dynamics in tillage (e.g. Gill and Berg, 1968; McKyes, 1985) and tillage erosion (e.g. Mech and Free, 1942; Govers et al., 1994; Lobb and Kachanoski, 1999). Soil dynamics in tillage was well studied; but no literature was found on studying straw movement by tillage. Tracer methods for measuring soil movement were developed in the study of tillage erosion. Studies on soil mechanics and soil erosion did not include the effect of straw on soil movement. No sufficient data are currently available. Thus, detailed study on tillage tool–soil–crop residue interaction is needed to understand this interaction and develop new models.

Soil bin is used for studying tool and soil interaction since it would be too hard to control parameters and clearly explain soil and tool interaction in a fieldwork. Soil bin experiments were designed and conducted in this study. A field experiment was also conducted to compare with the results from the soil bin experiments.

Cereals are major crops and high-residue producers in Canadian Prairie Provinces. A sweep type tool was selected due to its popularity in these provinces. The goal of this study was to better understand the process of tillage tool–soil–crop residue interaction under controlled conditions. The objectives of this study were:

a) To compare the experimental methods of measuring straw movement in a soil bin;

b) To study effect of straw length and tillage speed on soil and straw movement, and straw burial; and,

c) To compare the results of a soil bin experiment with those of a field experiment.

2 MATERIALS AND METHODS

Three experiments were conducted in an indoor soil bin and a field to study tool-soil-straw interaction. Experimental factors include straw length, tillage speed, residue conditions, and tool arrangement. Tillage depth was the same for all three experiments. The soils in the soil bin and the field had a similar texture of loamy sand. Soil moisture content and bulk density were maintained at constant for all experimental runs in the soil bin. The moisture content of the field soil was kept similar as that of bin soil by watering.

2.1 Description of Experimental Field and the Soil Bin

2.1.1 Soil Bin

The soil bin is located at the University of Manitoba, Canada. The dimensions of the bin are 15 m long and 1.75 m wide. The bin is 0.5 m deep, and is filled with loamy sand soil to a depth of 0.4 m. A tool carriage is supported by two rails on each side of the bin. The maximum travel speed of the carriage is 10 km/h. A full width rotary tiller drawn by the carriage is used for tilling through the width and length of the soil bin to loosen soil. An iron plate and a plain roller, which can be mounted on the carriage, are used for levelling and packing the soil.

2.1.2 Field

An oat field of 60-m by 100-m, located at the Carman Research Station in Carman, Manitoba (Canada), was selected as the experimental field. Oats were harvested and the standing stubble of 150 to 180-mm-high was left. Oats were also planted in the preceding year. The field was divided into 14 4-m-wide and 40-m-long blocks along the direction perpendicular to the planting rows, and each block contained 3 plots. The travel direction of tillage was perpendicular to the planting rows for all tillage operations.

2.2 Tillage Tool and Its Operations

A 325-mm-wide sweep (50-12K, Mckay Canada) and a C-shank were employed in both the soil bin and field experiments. The configuration of this tool is shown in Fig. 1. Tillage depth was 100 mm.

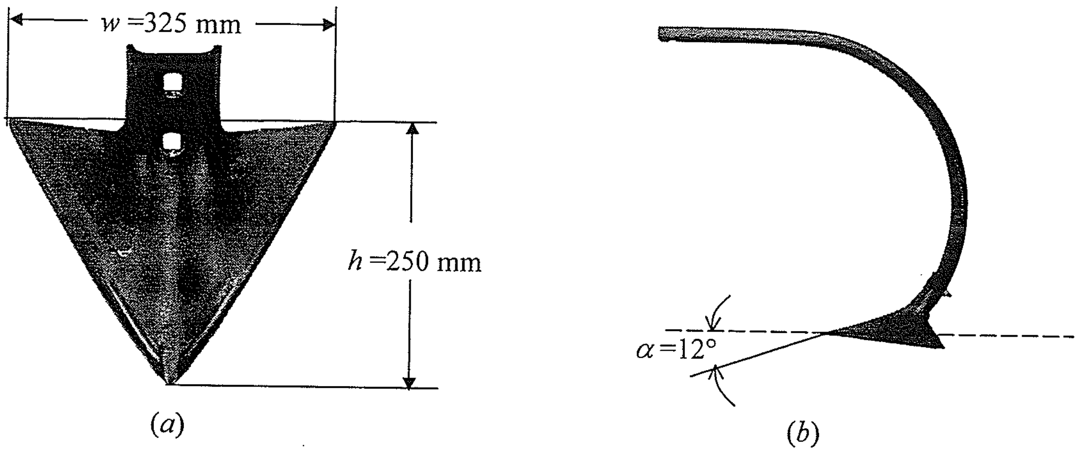


Figure 1. Tool configuration; (*a*) the sweep (McKay 50-12K); (*b*) the sweep and shank

Three tillage operations were employed: (1) one pass with a single tool; (2) three parallel passes with a single tool; and (3) one pass with three tools. The spacings of the three tools were set as shown in Fig. 2. There were neither gap nor overlap between two adjacent tools. For the three parallel passes, the three tools represented three passes respectively (Fig. 2). For the one pass with a single tool, the tool 1 was the tool position.

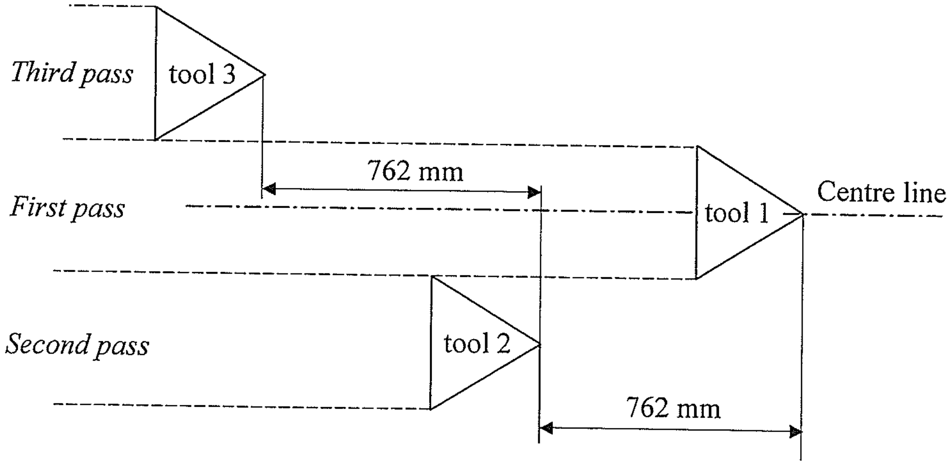


Figure 2. Arrangement of three parallel passes and three tools

A field tool unit was designed and fabricated for the field experiment. It has the capacity of installing 3 tools (Fig. 3). The tool unit has four wheels; it can be drawn by a tractor through a one-point hitch. Four arms that form a parallel four-lever mechanism connected the inner frame to the outer frame. The hydraulic cylinder installed between the inner frame and an arm was operated by a tractor's power take-off to adjust the tillage depth. Tools were mounted on the tool bars of the inner frame, and the tool spacing was set as indicated in Fig. 2.

For the soil bin experiments, three tools were mounted on the tool bar of the carriage (Fig. 4) though L-frames specially made to achieve identical tool spacings with the field tool unit.

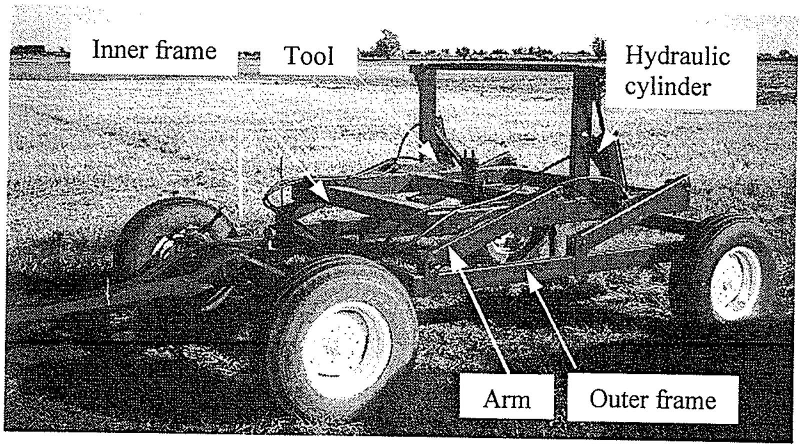


Figure 3. A tool unit used for the field experiment

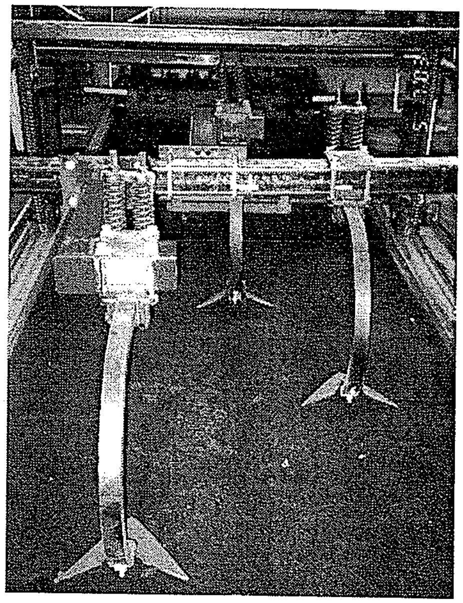


Figure 4. Three-tool unit used in the soil bin experiment

2.3 Experiments and Conditions

2.3.1 Straw

Oat straw was used to represent crop residue. Straw was cut into nine different lengths from 50 to 250 mm with increments of 25 mm, and stored separately. Straw mixture of different lengths of straw was considered as a mean to reduce the number of test runs. Thus, three straw mixtures were adopted to examine if a straw mixture could represent those single lengths. Straw mixture 1 was a mixture of 50, 125, and 200-mm-long pieces of straw; mixture 2 consisted of 75, 150, and 225-mm-long pieces of straw; and 100, 175, and 250-mm-long pieces of straw were included into mixture 3. Each mixture had a total of 300 pieces, and 100 pieces of each length.

In both field and soil bin experiments, straw pieces were manually applied and laid flat on the soil surface to represent crop residue. This straw condition is referred to as flat straw hereafter. When using straw mixtures, there could be a possibility that the different lengths impact one on another. To examine this impact, plots with single-sized straw (all straw pieces were the same length) were also designed in the soil bin experiment.

2.3.2 Experimental Design

Completely block design was used. For soil bin experiment, each block was assigned in one tillage run due to each test run could only arrange three plots. All treatments were replicated three times.

Experiment 1 was carried out in the soil bin to measure soil and straw displacement and straw burial with a single sweep. There were no crop residues at all in the soil bin before applying the flat straw. This experiment consisted of three sections. Section 1 was to acquire basic data of soil and straw displacement, and straw burial. It was conducted with one-pass tillage of a single tool at the speed of 5 km/h. The flat straw applied included three straw mixtures. Section 2 was designed for the purposes of comparing experimental methods, such as comparing the straw displacement using straw mixtures as a flat straw with that using single-sized straw. The treatments were flat straw conditions: three straw mixtures and nine single lengths. Section 3 was to study the effect of tillage speed on soil and straw displacement using three straw mixtures at three speeds, which was a nine-treatment experiment.

Experiment 2 was to repeat the experiment 1 under field conditions at one tillage speed in order to compare with the results of the soil bin experiment. There were two residue conditions in the field. Condition 1 was designed to recognize the differences of soil and straw movement between field soil and bin soil. For this purpose, all the crop residues on the soil surface were completely removed beforehand, and then flat straw was manually applied. Hence, major differences between the field soil and the bin soil were that there were roots and other organic matter in the field soil; and, the bin soil was disturbed and pure soil. Condition 2: standing stubble was kept and all other crop residues on the soil surface were removed, and then flat straw was manually applied as was done in Condition 1. Condition 2 was designed to study the effect of standing stubble on soil and straw movement.

Three lengths of straw were used in experiment 2. Tillage operation included one pass with a single tool, and one pass with three tools. Therefore, there were twelve treatments in total. Compared to the three parallel passes in experiment 1, three tools were used in the field experiment due to the difficulty in repeating three parallel passes in a field. This operational difference could impact experimental results when repeating the experiment 1 in a field. Therefore, the experiment 3 was conducted to recognize the operational conditions in the field and the soil bin. It was also carried out in the soil bin used in the experiment 1 with the same three lengths of straw as those in experiment 2. Tillage operations with one tool and three tools, as well as three lengths of flat straw were the same as those used in experiment 2 that was six treatments. Detailed experimental parameters for all experiments are listed in Table 1.

Table 1. Experimental Parameters

Variable parameters	**Experiment 1** (soil bin)			**Experiment 2** (Field)	**Experiment 3** (Soil bin)
	Section 1	Section 2	Section 3		
Tillage speed (km/h)	5	5	5, 7.5, 10	5	
Straw length (mm)	3 Mixtures	3 Mixtures 9 lengths	3 Mixtures	3 lengths (100, 175, 250)	
Residue conditions	Flat straw			2 Conditions	Flat straw
Tillage pass	1pass with 1 tool	3 Parallel passes		1 pass with 1 tool; 1 pass with 3 tools	
Constant parameters					
Tillage depth (mm)	100				
Straw mass (kg/m^2)	0.108				
Tool	325-mm-wide sweep				
Soil texture	Loamy sand				
Soil moisture content (%)	15 – 18				
Soil bulk density (kg/m^3)	1220			1330	1220

2.4 Plot and Tracer

Point tracers are individually labelled objects of various shapes and materials, which have the distinct advantage to characterize complex movement in three dimensions. For this reason, point tracers were employed in a plot to measure soil and straw displacement. All tracers were set up, and their initial positions were recorded. Then, flat straw was manually applied on the top of all tracers forming a plot. A plot was defined as the area of straw applied on the soil surface. Every plot in both field and soil bin experiments had the same width of 0.975 m, which was three times the tool width. The centre line of the first tool or the first pass was also the centre line of the plot in length. To easily measure soil and straw movement as well as straw incorporation, the minimum length of a plot was 1.5 m long. The movement of the soil and straw located in the central third of a plot (the path of the first pass shown in Fig. 2) over its length were traced during tillage operation. All tracers were situated in the central third of a plot over the first half of its length, and the second half of its length was used to measure straw incorporation.

Nine aluminium cubes of 1 cm^3 were used as soil tracers, and they were arranged in a line perpendicular to the direction of tool travel. These distinguishing cubes were inserted into the soil, and the top surfaces of them were made even with the soil surface to trace the movement of the surface soil, as shown in Fig. 5. Straw tracers were specific lengths of straw pieces, which were laid flat on the soil surface. Every straw tracer had a distinguishing central mark. The lengths of straw tracers in a plot were the same as those flat straw applied. For a plot with a straw mixture, three lengths of straw tracers were then used to trace the movement of each component. For any length, straw tracers were laterally and longitudinally oriented. The longitudinal tracers were parallel to the direction of tool travel, and the lateral ones were perpendicular to the travel direction. The results of straw displacement measured with these two tracer orientations will be compared.

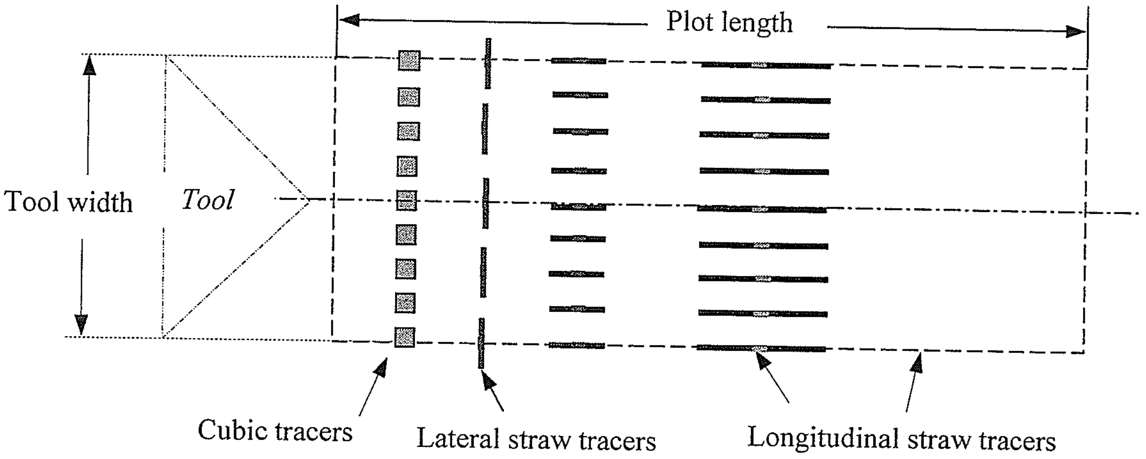


Figure 5. Examples of cubic and straw tracers in the central third area of a plot

2.5 Measurements

In experiment 1, the central third of a plot over its length (central area) and its adjacent areas were the same straw mixture applied, but the straw in the central area had different colour than the others. Therefore, straw pieces originally situated in the central area were easy to be recognized after tillage. The following measurements were taken:

- The state of burial of each individual straw before and after tillage;
- Soil and straw displacement;
- Soil profile after tillage.

For experiments 2 and 3, measurements included:

- Soil and straw displacement; and,
- Straw coverage by photographing before and after tillage.

To set up and measure the tracers' positions before and after tillage, a device (Fig. 6), which has four wheels and could freely slide along the rails of the bin, was made for the soil bin experiments. A type measurer was attached to read lateral displacements. To measure the displacement of tracers in the field, a 2.4-m-long and 1.8-m-wide wooden frame was made to support the device used in the soil bin experiment (Fig. 7). There were two wheels on the one end of this frame, and two fixed stands on the other end. One could move it easily and it would stay still. Two 2.4-m-long steel angles were mounted on the side beams to guide the device. A pointer could laterally slide along the device. To read the longitudinal positions, a tape measurer was attached on one steel angle.

Video cameras were mounted on the top, front, and lateral positions of the tool during experiment for assisting data analysis and interpretation of results.

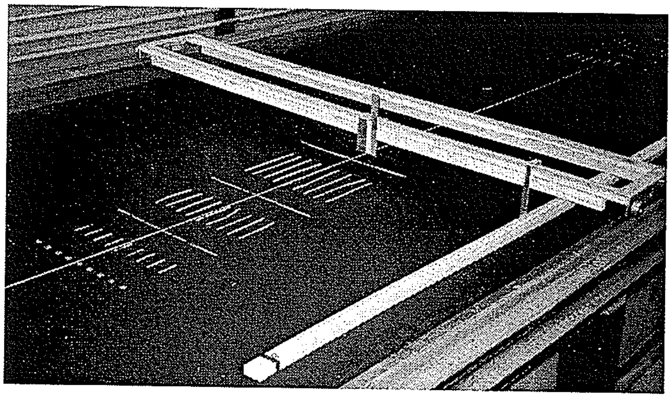


Figure 6. Arrangement of the tracers in a plot and the device used

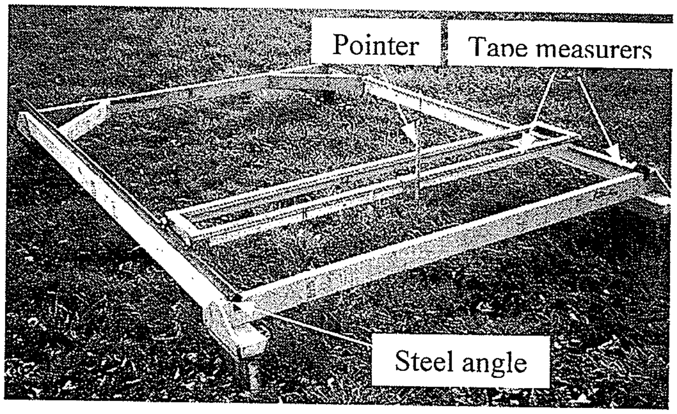


Figure 7. A device for measuring the displacement of soil and straw in the field

2.6 Data Analysis

Experimental data were analyzed to detect significant difference by ANOVA with Duncan test at significance level of 0.1 except the value specially indicated. The software used was ANOVA procedure in SAS windows v 8.0. Standard deviation of three replications was used as error bars in the results. Presented bars in any bar graph without a common letter above them differ significantly, and these significances were detected by comparing means with one-way ANOVA. Other specific methods will be indicated.

3 RESULTS AND DISCUSSION

The soil moisture and bulk density were monitored for each test run by taking three soil samples in each plot. The soil samples were weighted and then dried in an oven at temperature of 105°C for 24 h. The average moisture content of the bin soil was 16.3% with standard deviation of 1.2%, and the mean of (dry mass) bulk densities was 1220kg/m^3 with standard deviation of 56 kg/m^3 over the entire experiment. Average moisture content of the field soil was 18.4% with standard variation of 2.8%. The average bulk density of the field soil was 1330 kg/m^3 with standard deviation of 80 kg/m^3.

3.1 Experimental Methods

Study of experimental method was conducted in experiment 1. Tillage operation was three parallel passes at the speed of 5 km/h. The analysis below was based on the straw amount applied, which was treated as a constant in this study.

3.1.1 Impact of Different Lengths of Straw in a Straw Mixture on One Another

Two aspects of this impact were studied in the experiment 1 by comparing the results with the straw mixtures and single-sized straw. The first aspect was straw burial.

Compared to the results of single-sized straw, percent of unburied straw measured with the straw mixture was significantly different for 125 mm straw and shorter, and 175-mm-long straw as well (Fig. 8). The longer straw pieces in the mixture could significantly affect the burial of those shorter ones.

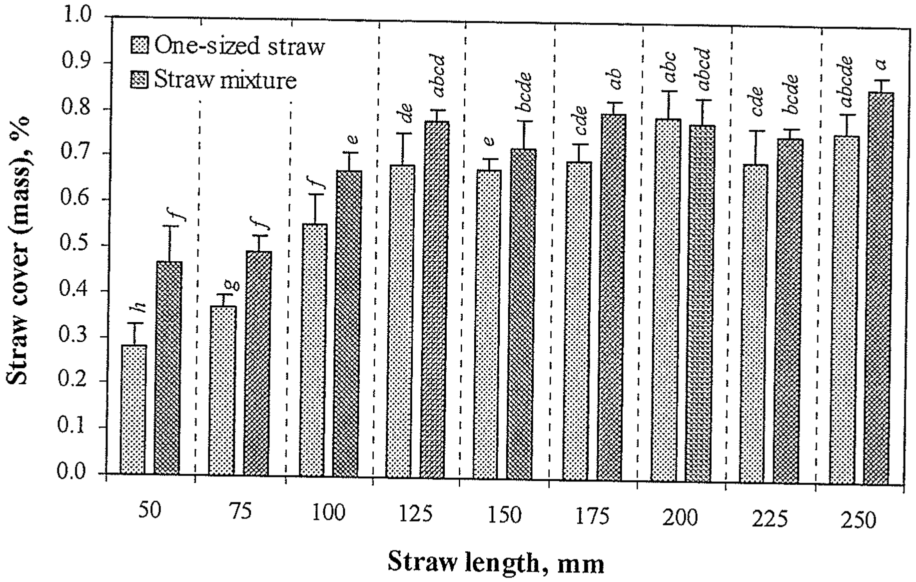


Figure 8. Comparison of straw cover for the plots with single-sized straw and straw mixture by tillage of three parallel passes at the speed of 5 km/h

The second aspect was straw displacement. The discussion here was based on results measured with longitudinal tracers, and forward displacement indicates the average forward displacement of nine tracers. The forward displacement of straw measured from those plots of straw mixtures were smaller than those measured from single-sized straw plots, but they were not significantly different for all lengths with one exception, 225 mm (Fig. 9). Sometimes, straw tracer was caught on the shank, and its forward displacement was then very large. Occasionally, a straw tracer was found on the shank when the tool carriage stopped. This is referred as to straw dragging. The straw dragging caused the large variance at the point of 225-mm-long straw.

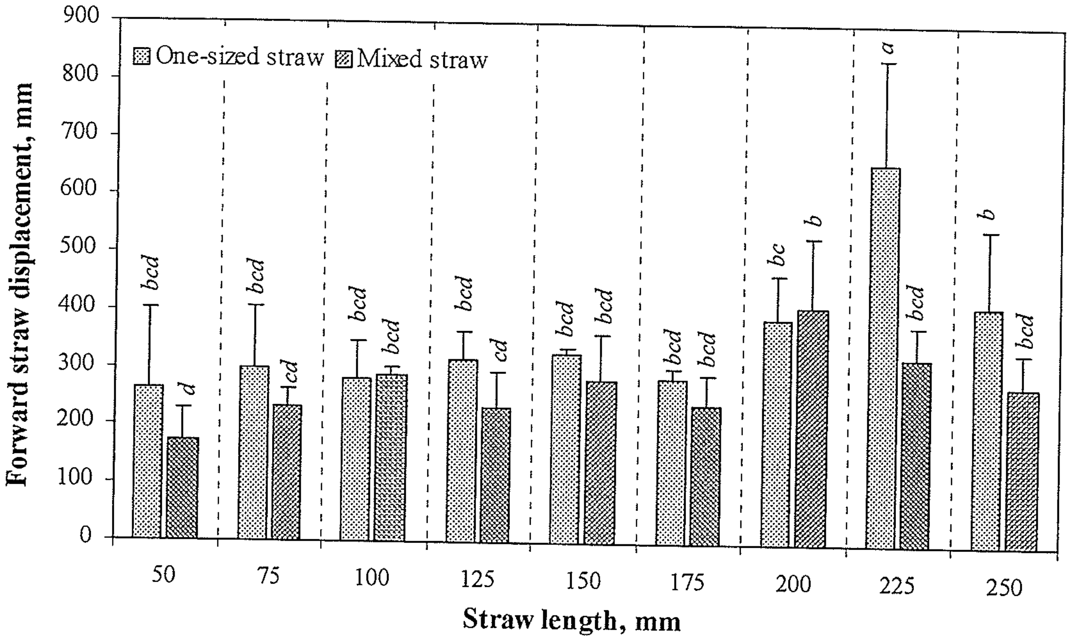


Figure 9. Comparison of forward straw displacement for the plots with single-sized and straw mixture by three parallel passes at the speed of 5 km/h

These results indicated that the interaction among different lengths of straw was not significant for most lengths. Therefore, it could be concluded that straw mixtures worked well in studying straw movement. However, to completely exclude the impact of different lengths of straw on one another, plots with single-sized straw would be better.

3.1.2 Comparison of the Results measured with Two Tracer Orientations

Figure 10 presents the forward straw displacement measured with longitudinal and lateral tracers in experiment 1 when the tillage operation was three parallel passes at the speed of 5 km/h. Straw was the three mixtures. The forward displacement measured with the longitudinal tracers was smaller than that measured with the lateral ones for most lengths of straw; but no significant differences were detected except one of 250-mm-long straw. The 250-mm-long tracers had the largest fluctuation, which was caused by straw dragging. The variances of displacement measured with lateral tracers were large. Compared to the longitudinal tracers, a much longer plot was required to properly arrange all lateral tracers, as it was impossible to laterally arrange nine tracers in a single line within one width of a tool. A very long plot would dramatically increase the experimental time and the difficulty of field measurements. For this reason, the longitudinal tracers were employed in experiments 2 and 3.

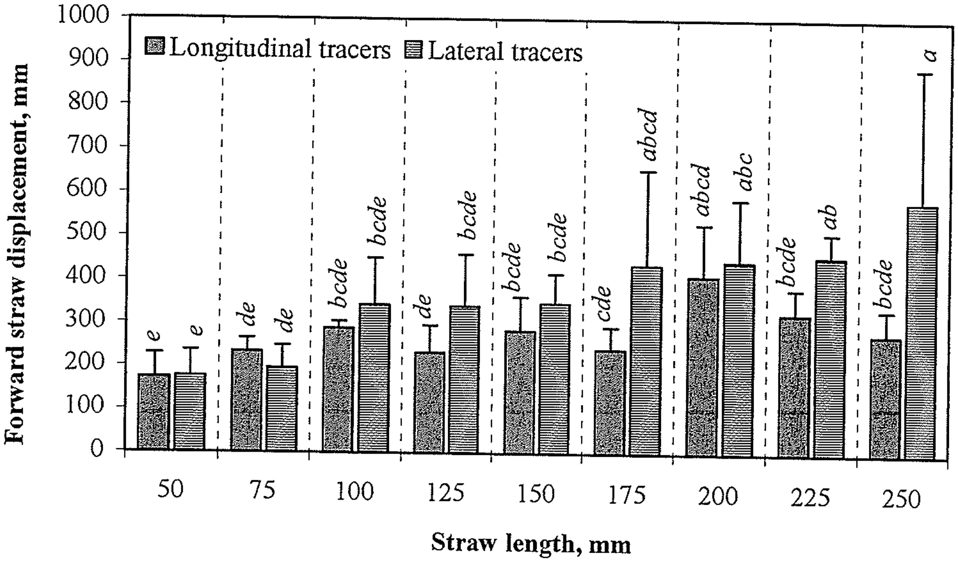


Figure 10. Comparison of forward straw displacement measured with longitudinal and lateral tracers by the tillage (5 km/h) of three parallel passes

3.2 Forward Soil Displacement

3.2.1 One Tillage Pass with a Single Tool

Soil forward displacement decreases with increasing straw length for both experiments 2 and 3 (Fig. 11). The forward displacement of the field soil was 50% and greater than that of the bin soil for all three lengths of straw when there was only flat straw in the field (residue condition 1). The differences between the field soil and the bin soil, such as crop roots and soil bulk densities, could be the major reason caused the difference of soil displacement. Roots in the field soil may hold soil to form root balls that could increase soil rolling; and higher soil density of the field soil might also contribute to the soil rolling. This can be proved by the greater width of soil disturbance in the field. In addition, the stronger vibration of the field tool unit could also increase soil displacement compared to the stable carriage of the soil bin.

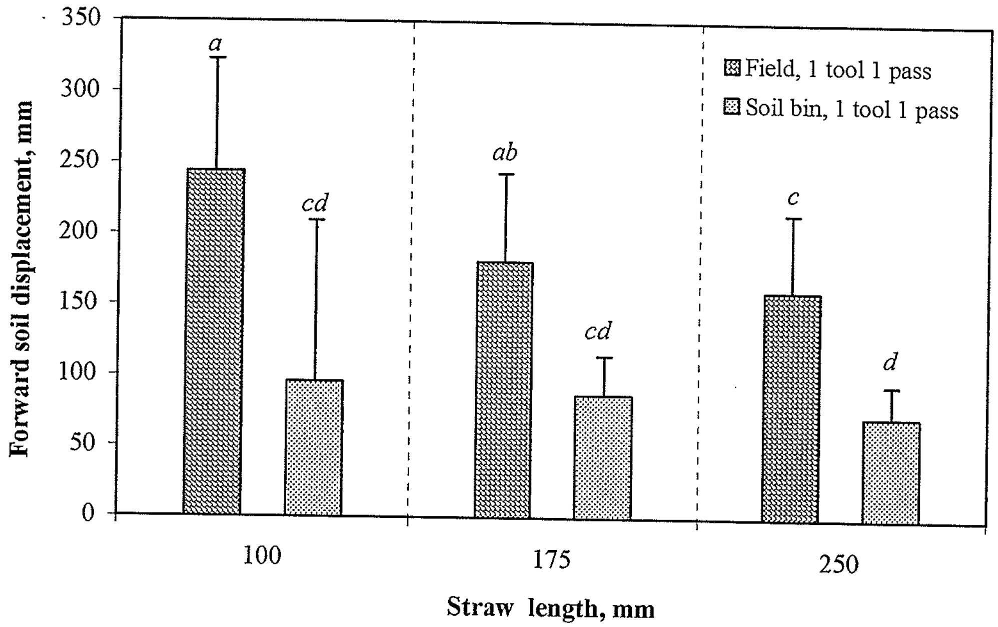


Figure 11. Comparison of forward soil displacement measured in the field (flat straw only) and soil bin by one pass tillage with a single tool at 5 km/h

3.2.2 Tillage Operation with Three Tools

Forward soil displacement by one pass of three tools numerically decreased with increasing straw length (Fig. 12). Forward soil displacement measured in the soil bin with three tools and three parallel passes showed that three tools produced larger soil displacement than three parallel passes; but, statistical analysis did not detect any significant differences between three tools and three parallel passes at the speed of 5 km/h. It also indicated that there was an interaction between tools impacting soil movement. In other words, other tools could impact the soil moved by a tool while the soil was still moving. However, this interaction depends on tillage speed and tool spacings. Observational runs were conducted using speeds of 1, 3, and 5 km/h. The video of soil and straw motion in front of tools showed that the interaction between adjacent tools would not occur when the speed was slower than 3 km/h for the tool spacings used.

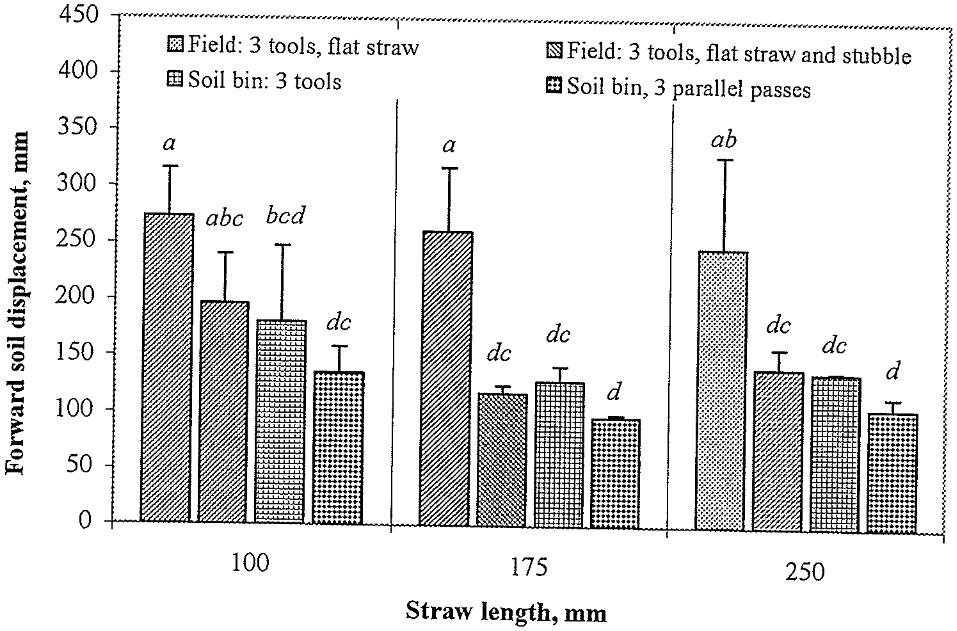


Figure 12. Comparison of forward soil displacement by three tools in the soil bin and field, and three parallel passes in the soil bin (tillage speed: 5/km/h)

3.2.3 Effect of Standing Stubble on Soil Movement

The effect of standing stubble on soil movement was also given in Fig. 12. As discussed above, soil displacement in the field was larger than that in the soil bin, and it was rationalised that the field soil rolls more than that of the bin soil. The effect of standing stubble on soil displacement, as shown in Fig. 12, strongly supports this explanation. When standing stubble existed, the soil displacement in the field was very close to that of the soil bin, and no significant difference was detected. Standing stubble effectively reduced the rolling displacement of soil at the speed of 5 km/h. Results in Fig. 12 also indicated that longer straw pieces were more effective than shorter ones in reducing soil displacement.

3.3 Forward Straw Displacement

3.3.1 One Tillage Pass with a Single Tool

The tillage operation of one-pass with a single tool was carried out in both field and soil bin. Results showed that the forward straw displacement slightly increased with increased straw length; but this increasing trend was not significant (Fig. 13). For the field experiment, the forward displacement of straw significantly increased when straw length increased from 175 mm to 250 mm. The results of the field experiment under flat straw condition had larger variances compared to those of soil bin experiment, and the variances became larger when straw length increased. Large differences of forward soil displacement between the field and soil bin experiments were found; comparatively, the forward displacements of straw measured in the field and soil bin were very close. This also suggested that larger forward displacement of the field soil was caused by soil rolling because straw does not generally roll.

3.3.2 Tillage Operation of Three Tools

After tillage operation with three tools, the forward displacement of straw measured in the field and the soil bin were close and following the same trend (Fig. 14). Forward straw displacement by three parallel passes with a single tool varied in a concave shape with increasing straw length, but it was not statistically different compared to the results of field and soil experiments using three tools. Thus, the interaction between tools did not significantly affect the forward displacement of straw. It is also reasonable to conclude that this effect could be covered up by the large variance of measurements.

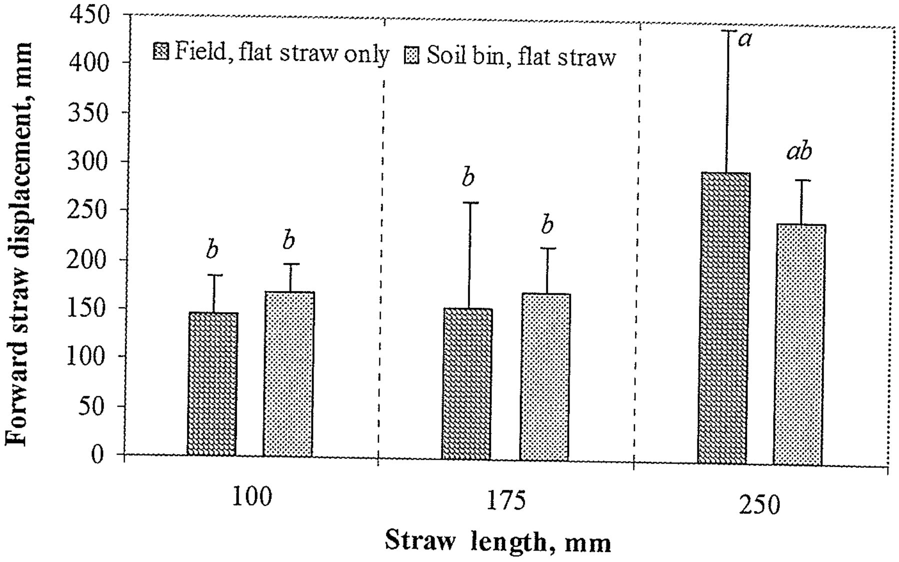


Figure 13. Forward straw displacement by one pass with a single tool in field and soil bin

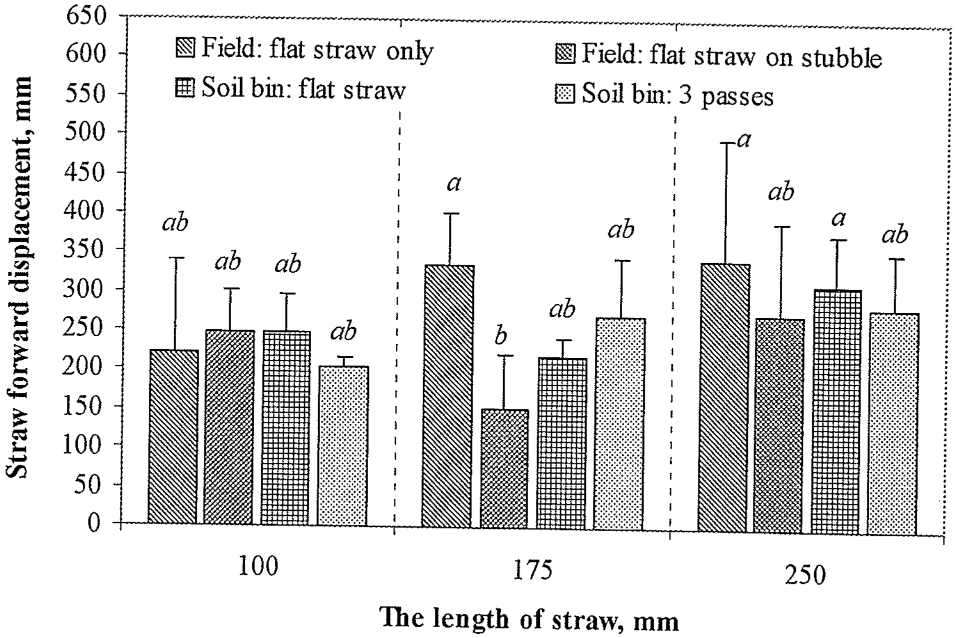


Figure 14. Comparison of forward straw displacement between experiment 1, 2 and 3 by tillage of three tools and three parallel passes

3.3.3 Effect of Standing Stubble

Figure 14 shows the forward straw displacement obtained from the field and soil bin experiments with three tools. The forward straw displacement seems to increase when straw length increased if there was no standing stubble. However, the forward displacement does not significantly differ for 100 and 250-mm-long straw pieces no matter where the displacement was measured. Standing stubble does not significantly affect straw displacement except 175-mm-long straw. The reason could be that straw length was accidentally close to the height of standing stubble, and this coincidence might make this specific length of straw move with standing stubble or the root balls.

3.4 Effect of Tillage Speed on Soil and Straw Displacement

3.4.1 Soil Displacement

The effect of tillage speed on soil and straw displacement was studied in experiment 1, and three straw mixtures were used. The results of soil displacement represented the effect of straw mixtures on soil movement. The average lengths of three straw mixtures were ascending. The forward displacement of soil increased with increasing tillage speed (Fig. 15). Forward soil displacement significantly increased with increased average length of straw pieces in a mixture at the speed of 10 km/h. The forward displacement of soil at the speed of 5 km/h was significantly smaller than those at speeds of 7.5 and 10 km/h for all three mixtures. Increased tillage speed increased the forward displacement of soil no matter which straw mixture. The results indicate that the forward displacement of soil would be reduced 70% and greater if tillage speed was reduced from 10 km/h to 5 km/h no matter regardless of straw length.

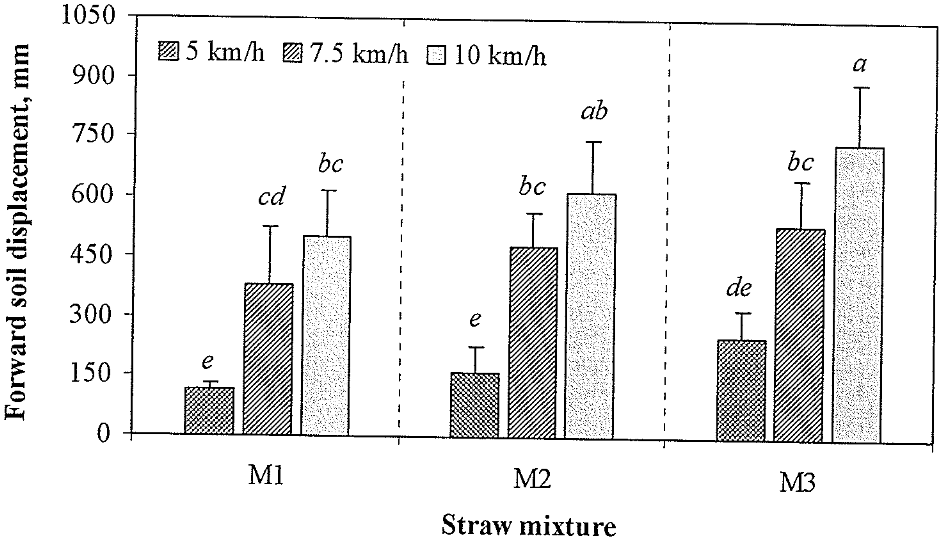


Figure 15. Comparison of soil forward displacement by three parallel passes at the speeds of 5, 7.5 and 10 km/h with a single tool

3.4.2 Straw Displacement

Figure 16 presents the forward straw displacement by three parallel passes for each length of straw. Standard deviation indicated the fluctuations of straw displacement were large. The video of the tillage process discovered that the straw dragging caused the large variation. Besides, straw tracer had a chance to fall into the furrow through a crack on the soil surface, so the displacement of this tracer would be small.

It looks that forward straw displacement increased when straw length increased; but statistical analysis by two-way ANOVA with Duncan test at significant level of 0.1 indicated that there was no significant trend of increasing as shown by those letters followed the straw lengths in Fig. 16. However, tillage speed significantly affected straw displacement. The average forward straw displacements of all lengths were significantly different at three speeds. The overall average forward displacement of nine lengths was

273 ± 63 mm at the speed of 5 km/h, and 656 ±106 and 1033 ±189 mm at 7.5 and 10 km/h respectively. Thus, slower speed could effectively reduce straw displacement.

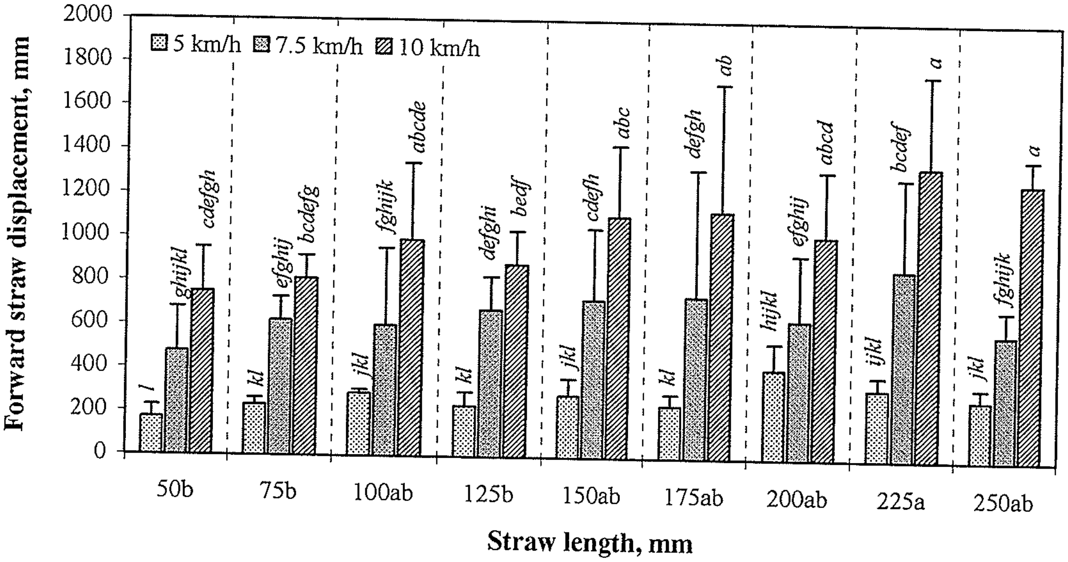


Figure 16. Forward straw displacement at speeds of 5, 7.5, and 10 km/h by three parallel passes with a single tool in the soil bin

(Letters followed the straw length shows the significant differences between straw lengths. It was tested by two-way ANOVA with Duncan test at significant level of 0.1)

3.4.3 Lateral Straw Displacement

Tillage speed also affected the lateral displacement of soil and straw. Measurements of soil disturbance in the soil bin experiment indicated that tillage speed significantly increased soil lateral displacement. The width of soil disturbance after one tillage pass at speeds of 5, 7.5, and 10 km/h were 716, 824, and 976 mm respectively. Straw disturbance was not easily measured, but straw tracer distribution also showed the lateral displacement of straw. For example, figure 17 shows the two-dimensional distributions of 100-mm-long straw tracers after three parallel passes at three speeds. Higher tillage speeds resulted in straw being distributed in a larger area.

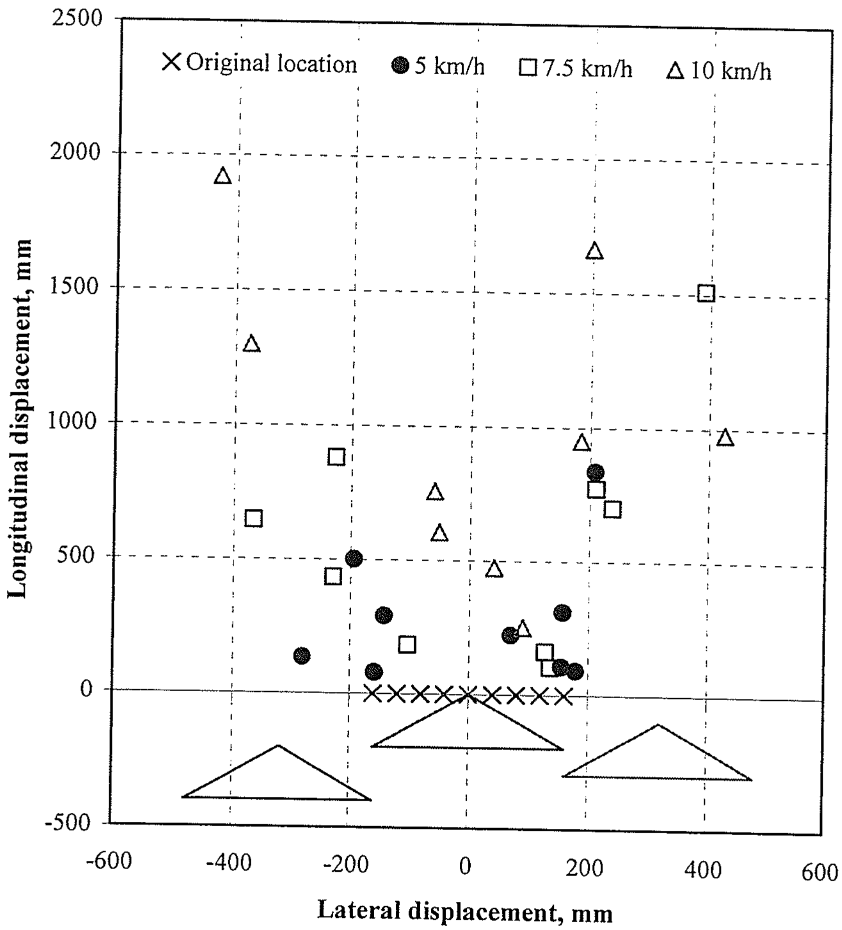


Figure 17. The distribution of straw tracers by three parallel passes with a single tool at three speeds (Lateral coordinate is zero represents the centre line of the first pass)

3.5 Straw Incorporation

3.5.1 Effect of Tillage Speed on Straw Burial

The effect of speed on straw burial was studied in the soil bin experiment with the tillage of three parallel passes. The burial conditions of all straw pieces originally applied in the central third of a plot over its length were individually measured. The results indicated that lower speeds bury less straw than higher speeds. Unburied straw percent at three speeds is shown in Fig. 18. The percent of unburied straw significantly decreased when tillage speed increased from 5 to 10 km/h regardless of the straw length. For all straw lengths, there was 45% to 85% of straw by mass left on the surface after three parallel passes at 5 km/h. If increasing speed to 10 km/h, unburied straw was then reduced to 25% to 40%. The percents of unburied straw at three speeds of 5, 7.5 and 10 km/h were significantly different when the length of straw was longer than 150 mm.

To show the relationship between unburied straw and straw length at each individual speed, linear correlation of the relationship between unburied straw percent (P) and straw length (L) shown in Fig. 18 was analyzed. The three linear relationships are:

$$\begin{cases} P_1 = 4.4L + 48.5 & (5\,km/h, \quad R^2 = 0.75) \\ P_2 = 3.1L + 34.6 & (7.5km/h, \quad R^2 = 0.85) \\ P_3 = 2.1L + 28.3 & (10km/h, \quad R^2 = 0.76) \end{cases} \tag{1}$$

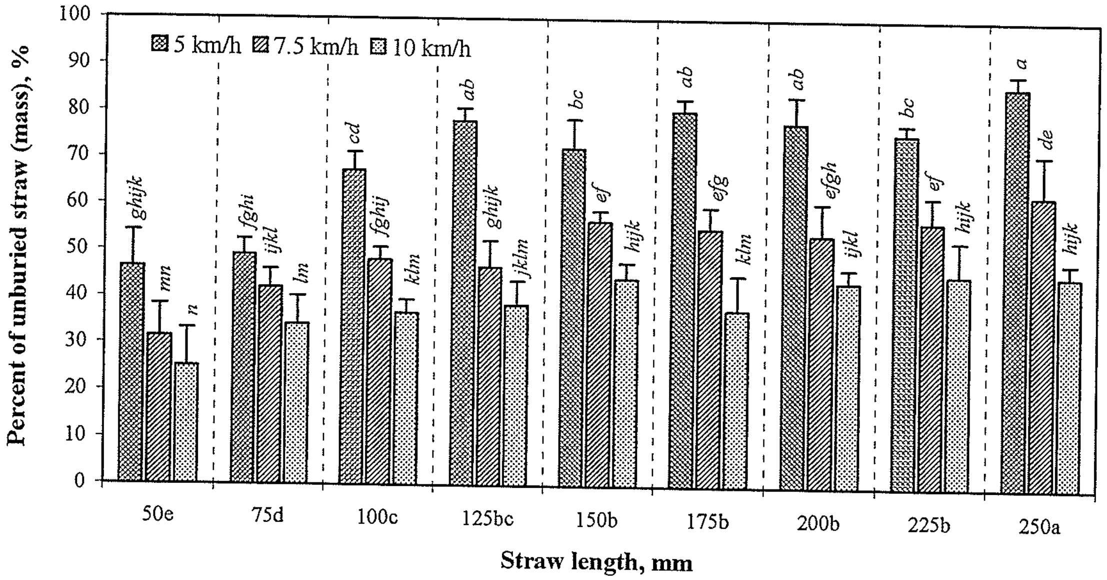


Figure 18. Relationship of the percent of unburied straw mass and straw length after tillage of three parallel passes at the speeds of 5, 7.5, and 10 km/h with a single tool

(Letters followed the straw length shows the significant differences between straw lengths. It was tested by two-way ANOVA with Duncan test at significant level of 0.1)

The percent of unburied straw increased with increasing straw length, and the increasing rates reduced when tillage speed increased. The unburied straw at the speed of 5 km/h was more sensitive to the changes of straw length compared to the speed of 10 km/h. The percent of unburied straw increased about 50% when tillage speed decreased from 10 to 5 km/h for any length of straw. The relationship between unburied straw, and speed and straw length was analyzed with factorial regression analysis (REG procedure) in SAS. Considering the interaction of straw length and speed, the overall $F = 114.07$ statistic was significant, and the R-square was 0.82, but the interaction term was not significant. When the interaction term was removed, the overall $F=153.15$ statistic was also significant. R-square was 0.80. The regression relationship of unburied straw (USP) and tillage speed and straw length is:

$$USP = 81.12 - 6.29 Speed + 3.20 Length \tag{2}$$

3.5.2 Straw Cover Percent

The cover percent of straw was measured in experiments 2 and 3 by photographing a square area (650 mm by 650 mm) between the second and third furrow after tillage operation with three tools. Straw covers before and after tillage were calculated to compare the field and soil bin operations. Values in Fig. 19 show the ratio of straw cover percents before and after tillage under the three conditions of soil with flat straw, field with flat straw, and field with flat straw and standing stubble. The common trend is that the cover percent increases with increased straw length for these three cases, and this increasing trend is linear for both soil bin and field experiments (experiments 1 and 3).

For 100 and 175-mm-long straw, the straw cover percents measured in the experiment 3 were not significantly different compared to those measured in experiment 2 no matter if stubble existed. It was concluded that the soil bin could be used to simulate field conditions in the study of soil and crop residue interaction if the length of straw was shorter than 250 mm.

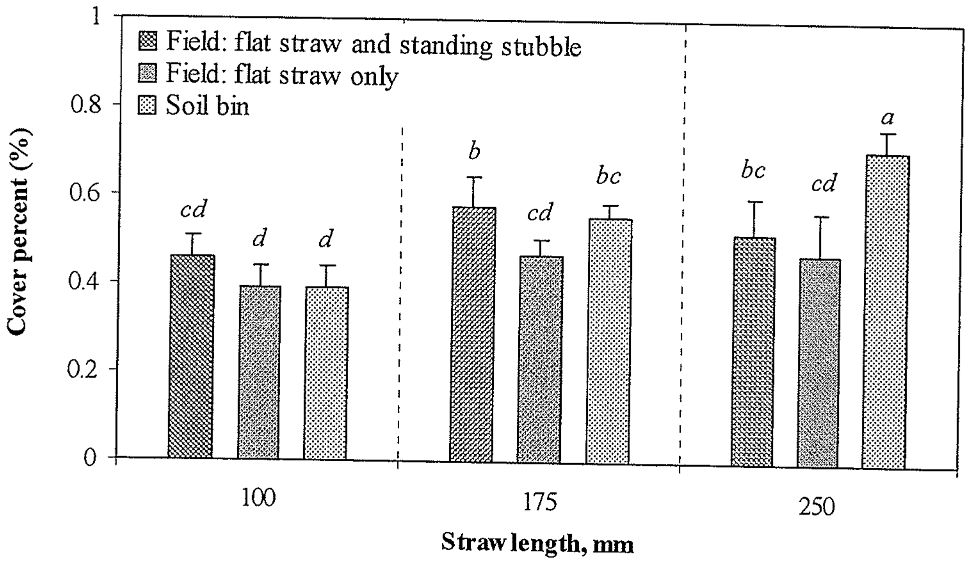


Figure 19. Straw covers after tillage with three tools at the speed of 5 km/h

4 CONCLUSIONS

Experimental study on the interaction of tillage tool–soil–straw was conducted in the soil bin and field with a 325-mm-wide sweep. Conclusions are:

1. Straw tracers were able to represent the movement of straw, and their orientations do not significantly affect the results. Straw mixtures worked well in studying soil and straw interaction. Straw burial measured with single-sized straw did not significantly differ with that measured with straw mixtures for most lengths of straw except those shorter than 100 mm.

2. Three parallel passes with a single tool was used to simulate three tools, but it produced less soil and straw displacement than using three tools for both soil bin and field experiments; but, there was no significant difference detected between the three parallel passes and three tools with Duncan test at significant level of 0.1.

3. No significant differences were detected for straw displacements measured in the field and the soil bin even when the field had standing stubble. Longer straw had larger displacement. Straw displacement had large variances, which could be a reflection of the differences between the measurements in the field and soil bin.

4. The forward displacement of the field soil was 50% greater than that of the bin soil when the field had no stubble. Standing stubble effectively reduced soil displacement at the speed of 5 km/h. The soil displacement in the stubble field was very close to that in the soil bin. Soil displacement was also reduced when increasing straw length, but it was not significantly different.

5. Soil and straw movement, and straw burial were very sensitive to the speed of tillage. The forward displacement of soil and straw reduced more than 70% and 80% respectively if tillage speed was reduced from 10 to 5 km/h.

6. For those straw pieces longer than 100 mm, increasing length did not significantly increase the percent of unburied straw no matter what the tillage speed was. For a specific length, the percent of unburied straw was significantly reduced when tillage speed increases.

7. The straw cover after tillage by three tools had a common trend of increasing with increased straw length, and this trend was linear for both the soil bin and the field

(without standing stubble) experiments. The straw covers measured in the soil bin were not significantly different compared to those measured in the field except one of 250-mm-long straw. It is concluded that the soil bin could be used to simulate the field conditions in study of straw incorporation if the length of straw was shorter than 250 mm.

5 REFERENCES

Chen, Y., F. Monero, D. Lobb, S. Tessier and C. Cavers. 2004. Effects of six tillage methods on residue incorporation and crop performance under a heavy clay soil condition. *Transactions of ASAE.* In press.

Gill, W. R. and G. E. V. Berg, 1968. *Soil dynamics in tillage and traction.* Agriculture Research Service. Washington D. C., Department of Agriculture, US.

Govers, Gerard; Vandaele, K.; Desmet, Phillipe. J.J; Poesen, Jean; Bunte, K. 1994. The role of tillage in soil redistribution on hillslopes. *European Journal of Soil Science*, *45*, 469-478.

Hanna, H. M., S. W. Melvin, R.O. Pope. 1995. Tillage implement operational effects on residue cover. *Applied Engineering in Agriculture*. 11(2): 205-210.

Lobb, D. A. and R. G. Kachanoski, 1999. Modelling tillage erosion on the topographically complex landscapes of southwestern Ontario. *Soil and Tillage Research*. 51: 261-277.

McKyes, E. 1985. *Soil cutting and tillage*. Elsevier Science Publishing Company Inc. 52 Vanderbilt Avenue, New York, NY10017, U.S.A

Mech, S. J. and G. R. Free. 1942. Movement of soil during tillage operation. *Agricultural Engineering*. 23(12): 379-382.

Woodruff, N. P. and W. S. Chepil. 1958. Influence of one-way-disk and surface-sweep tillage on factors affecting wind erosion. *Transactions of ASAE* 1:81-85.

Woodruff, N. P., C. R. Fenster, W. S. Chepil and F. H. Siddoway. 1965. Performance of tillage implements in a stubble mulch system. I. Residue conservation. *Agronomy Journal* 57: 45-49.

CHAPTER 3

Steady-State Models for the Movement of Soil and Straw during Tillage with a Single Sweep

ABSTRACT

A concept of steady-state movement, which mathematically describes the amount of the soil and straw moving by a sweep, was proposed. A sweep model for the steady-state movement of soil and straw in front of a sweep was developed and validated by an experiment conducted in an indoor soil bin using three different lengths of oat straw and a 325-mm-wide sweep. Existing soil-cutting models were also applied to the development of steady-state models. McKyes and Ali's (1977) model was selected as an example of three-dimensional model for narrow tools; and a two-dimensional model originally proposed for earth moving machines was selected for wide tools. The results of validation exercise indicated that these steady-state models would predict the amount of soil and straw moving during tillage with a sweep. When applying McKyes and Ali's model to calculate the amount of soil and straw moving by a sweep, it showed less accuracy than the sweep model. The possible reason was that McKyes and Ali's model was developed for a narrow blade but not a sweep. When using the two-dimensional model, the relative error was still larger than the sweep model. The relative error of the sweep model was 22% and less when predicting the amount of soil moving, and less than 12% if predicting the amount of straw moving by a sweep. Application of existing soil-cutting models to the steady-state movement of soil and straw needs further study.

1 INTRODUCTION

Tillage is used to prepare soil for seeding, reduce soil compaction, and handle crop residues. Tillage implements mechanically move soil and crop residues. Tillage practices are always accompanied by soil movement. The amount and distance of soil movement directly affect the rate of soil erosion; and a certain amount of soil moving is required to bury crop residues. However, unnecessary soil movement introduces extensive high consumption of energy. Therefore, understanding the amount of soil being moved is important for both managing tillage practices and designing new tillage tools to provide a desired amount of soil movement while reducing tillage erosion and energy requirements.

Soil movement by tillage has been studied in two research areas. The first area is the soil erosion related to tillage practices. The amount of soil moving and translocation can be calculated by the experimental soil distribution curve obtained using tracer method (e.g. Govers et al., 1994; Lobb et al., 1995; Lobb and Kachanoski, 1999; Lindstrom et al., 2000). These models were not physically based equations. The effect of tillage depth and speed was implicitly included. Sharifat (1999) developed a soil movement model according to the stress distribution of soil in front of a tool. The influences of soil parameters were treated as independent variables, and incorporated into the model by regression analysis. No literature was found on studying crop residue movement.

The second area is soil dynamics in tillage, where tillage and soil cutting has been studied for decades and soil-cutting models have been developed. These models were developed to describe the interaction between soil and tillage tool by studying soil failure in front of a tool. These achievements from 1912 to 1965 were well documented by Gill and Berg (1968). Other publications (e.g. McKyes, 1985; Koolen and Kuipers, 1983) described updated research achievements. Each of these models defines a soil failure zone, and provides the relationships of the forces acting on the tool.

The basic concept of the three-dimensional models is that the failure zone consists of three parts: one essential zone and two side zones. These models geometrically described the failure zone of soil during tillage. In other words, a soil mass with the volume of the failure zone exists in front of a tool at any moment during tillage, and the soil mass is the amount of soil moving at any instant. This is referred to as steady-state movement of soil (Liu et al., 2004). Thus, soil-cutting models could be applied to estimate the amount of soil moving, which is the volume of a soil failure zone, though these models do not predict the distance and the redistribution of soil after tillage.

Apparently, a connection between these two research areas has not been established. On the one hand, current methods of estimating the amount of soil moving were developed in the study of soil erosion, and they are based on experiments. On the other hand, these 3 dimensional soil-cutting models are physically based, and have not been used for studying the amount of soil moving.

To understand the amount of soil and straw moving by a tillage tool, physically based mathematical models are needed. These models can be used to simulate the process of soil movement for existing tools; and to forecast soil movement of a new tool to be designed. The goal of this research was to develop physically based mathematical models of the amount of soil and straw moving for both managing tillage practices and designing new tools to control soil movement with the purpose of reducing energy requirements and tillage erosion.

The objectives were:

a. To apply two existing soil-cutting models, McKyes and Ali's model and a two-dimensional model, to the study of the amount of soil and straw moving by a sweep;

b. To develop a new mathematical model for predicting the amount of soil and straw moving by a sweep; and

c. To validate these models with a soil bin experiment.

2 MODEL DEVELOPMENT

2.1 Conceptual Model Based on Experimental Observations

To observe soil and straw movement during tillage, an experiment was conducted in an indoor soil bin facility, which is located in the Department of Biosystems Engineering at the University of Manitoba (Canada). The dimensions of the bin are 15 m long and 1.75 m wide. The experimental length is about 13 m. Two rails on each side of the bin support a tool carriage, which is powered by a 7.46 kW electric motor equipped with speed control. The bin is 0.5 m deep, and is filled with loamy sand soil to a depth of 0.4 m. The average moisture content of the bin soil was 16.3% with standard deviation of 1.2%, and the dry bulk density was 1220 kg/m^3 with standard deviation of 60 kg/m^3 over the entire experiment. A full width rotary tiller drawn by the carriage is used for tilling through the width and length of the soil bin to loosen soil. An iron plate and a plain roller, which can be mounted on the carriage, are used for levelling and packing the soil.

A 325-mm-wide sweep was selected as a tillage tool (Fig. 1). Oat straw was used and cut into certain lengths, and then manually applied and laid flat on the soil surface to represent the surface crop residue. Soil and straw movement during tillage was recorded using video cameras mounted on the front, side, and top of the tool.

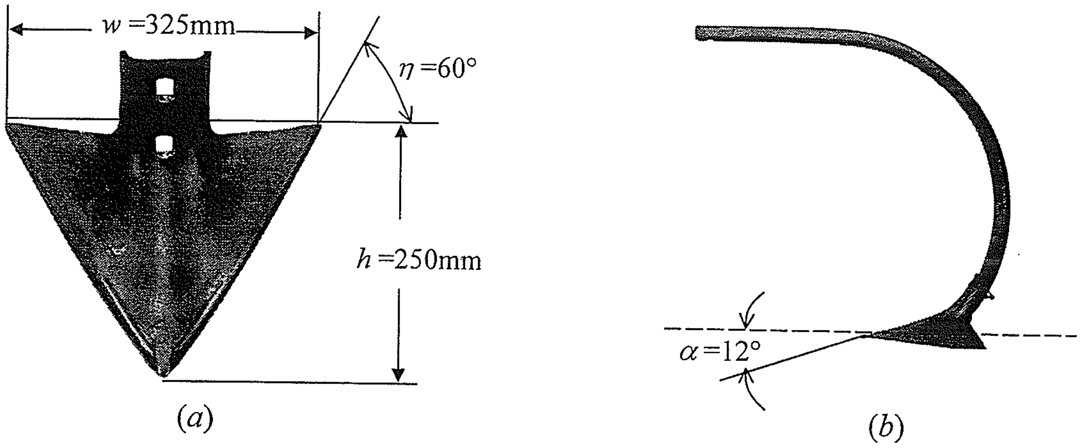


Figure 1. (*a*) The sweep (McKay 50-12K) and (*b*) the shank used in the experiment

A moving zone of soil in front of the tool was observed. The boundary between moving soil (within the zone) and static soil (beyond the zone) was clear. The soil inside the moving zone was considered as moving with the tool at any instant. Meanwhile, the soil moving was pushing the straw on its surface, moving it forward as well. The moving zone of straw was extended compared to the moving zone of soil due to the interaction among straw pieces. Hence, an extended moving zone of straw was formed and its size was related to the straw length.

2.2 Modeling the Amount of Soil Moving

2.2.1 Summary of Existing Soil-Cutting Models

There are two categories of existing soil-cutting models: two-dimensional and three-dimensional models. All three-dimensional models were developed for narrow tools; and two-dimensional models were originally developed for earth moving machines, which was treated as wide tools. The essential difference between models for wide and narrow tools is whether the side effect of the tool on soil movement was eliminated. Two side zones were included in three-dimensional models for narrow tools, but not in two-dimensional models for wide tools. The aspect ratio (tillage depth/tool width) is usually used for judging a tool is wide or narrow. However, it is relative whether a tool is a wide or narrow. There is no clear boundary between narrow and wide tools; or, if the side zones should be ignored. Therefore, two models for both narrow and wide tools were selected to study the suitability of modeling the amount of soil and straw moving.

2.2.2 McKyes and Ali's Model

McKyes and Ali (1977) developed a three-dimensional-wedge model (Fig. 2) without the need of experimental inputs of soil failure geometry. The size of soil failure zone depends on the width, depth and rake angle of a cutting blade, and soil properties. The centre zone (*ABCDEF*) has the same width as that of the blade. The side zone (*BDFG*) is a circular block with radius *r*. The distance *s* was shown in Fig. 2. The parameters *r* and *s* depend on the angle of soil failure β, which can be determined using parameters *d/w*, soil internal friction angle, and the frictional angle between soil and tool surface (McKyes, 1985). There are following relations to calculate the volume of the failure zone.

$$r/d = \cot\alpha + \cot\beta \tag{1}$$

$$s = d(\cot\alpha + \cot\beta)\left[1 - \left(\frac{\cot\alpha}{\cot\alpha + \cot\beta}\right)^2\right]^{1/2} \tag{2}$$

$$\theta = \arcsin\left[1 - \left(\frac{\cot\alpha}{\cot\alpha + \cot\beta}\right)^2\right]^{1/2} \tag{3}$$

where, $\beta =$ The angle of soil failure, which is determined by McKyes' method,

$\alpha =$ Rake angle of the blade,

$d =$ Depth of tillage, and

$w =$ Tool width.

The total volume of the moving zone is:

$$V = \frac{1}{2} w d^2 (\cot\alpha + \cot\beta) + \frac{1}{3} d^3 (\cot\alpha + \cot\beta)^2 \arcsin\left[1 - \left(\frac{\cot\alpha}{\cot\alpha + \cot\beta}\right)^2\right]^{1/2} \tag{4}$$

The angle β in Eq. 4 is the only undetermined parameter of soil failure, which can be determined by derivation equation $dN_\gamma / d\beta = 0$. Where N_γ is:

$$N_\gamma = \frac{\frac{1}{2}(\cot\alpha + \cot\beta)\left\{1 + \frac{2d}{3w}(\cot\alpha + \cot\beta)\left[1 - \frac{\cot^2\alpha}{(\cot\alpha + \cot\beta)^2}\right]^{\frac{1}{2}}\right\}}{\cos(\alpha + \delta) + \sin(\alpha + \delta)\cot(\beta + \phi)} \tag{5}$$

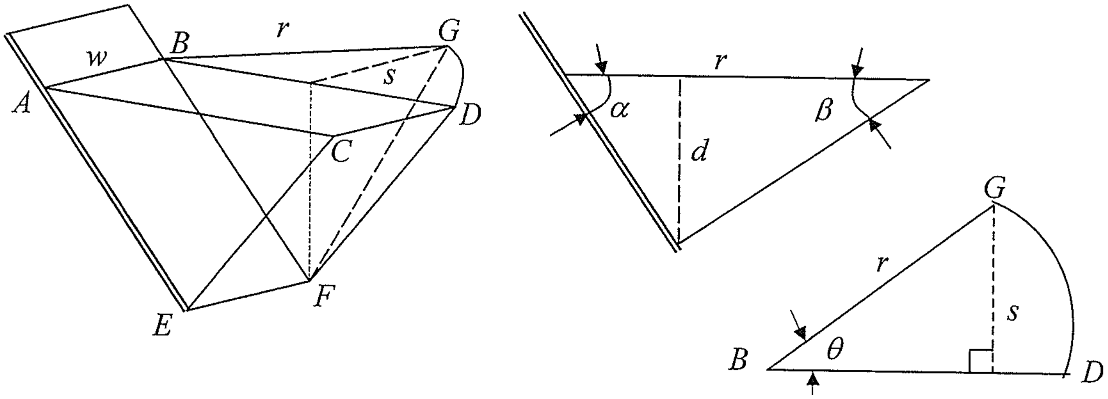


Figure 2. Three-dimensional model of soil cutting developed by McKyes and Ali (1977). The soil failure zone consists of one essential zone *ACDBEF* and two symmetrical side zones *BDGF*

2.2.3 A Two-Dimensional Model

For wide tools, the side zones can be neglected, and entire failure zone would be the centre zone with the same width as the tool. The failure line can be simplified as a straight line, and the wedge angle can be determined as McKyes suggested (McKyes, 1985). The volume of the failure zone or soil moving is the area of wedge *ABC* (Fig. 3) times the width of a tool:

$$V = \frac{1}{2} w d^2 (\cot\alpha + \cot\beta) \tag{6}$$

The soil failure angle (β), then, is calculated by the equation of N_γ factor:

$$N_\gamma = \frac{(\cot\alpha + \cot\beta)}{2[\cos(\alpha+\delta) + \sin(\alpha+\delta)\cot(\beta+\phi)]} \tag{7}$$

Equations 4 and 6 are the models of calculating the volume of soil moving by a tool. Tool width, rake angle, and tillage depth are major factors that determine the amount of soil moving. The mass of soil moving is the product of the volume and soil bulk density.

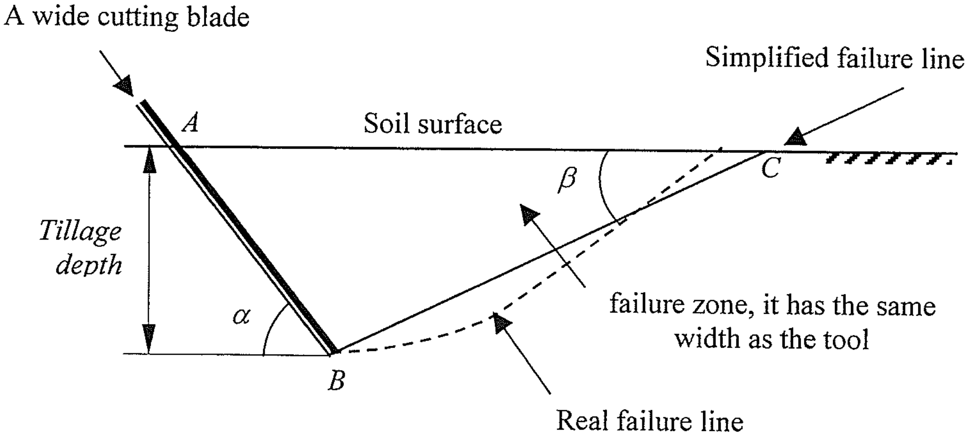
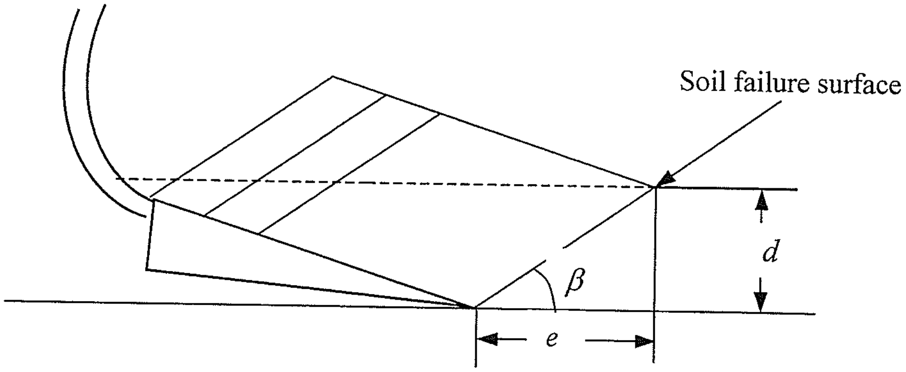


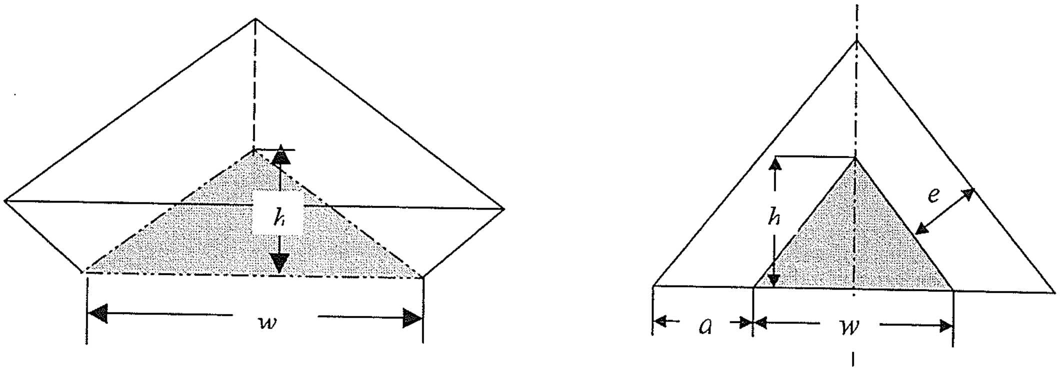
Figure 4. A two-dimensional soil-cutting model developed for earth moving machines

2.2.4 A Sweep Model

Different with the cutting blade, when a sweep cuts soil, soil fails and then slides along the surface of the sweep. For a sweep tool, the rake angle (α) is very small. It can be derived from Eq. 1 that the radius r would be very large when α is tending to very small. The actual soil failure pattern observed did not fit this result. The observed process of soil and tool interaction could be described as follows. When soil is cut, soil fails along a failure surface at the front edge of the tool and then slides onto the tool surface. Assuming that soil fails at two front edges of the sweep, and the angle of failure surface is β (Fig. 4a), which is the same as defined by Gill and Berg (1968). Then an analogous failure zone with the sweep was formed on the surface of the soil (Fig. 4b). The soil mass in the failure zone as shown in Fig. 4b was then lifted onto the surface of the sweep, and broken to fit the shape of the sweep. The volume of the failure zone was the amount of soil moving during tillage.



(a)



(b)

Figure 4. Assumptions of the soil moving zone in front of a sweep (a) Soil failure zone; (b) the volume of moving zone

The shape of this moving zone is a frustum of a pyramid with a triangle bottom. Compared to the bottom triangle, the surface is an extended triangle, and the extended length is:

$$e = \frac{d}{\tan\beta} \tag{8}$$

The volume of this failure zone is then:

$$V = \frac{hd}{6}\left(3w + \frac{6d\sqrt{h^2 + (w/2)^2}}{h\tan\beta} + \frac{4d^2\left(h^2 + (w/2)^2\right)}{wh^2\tan^2\beta}\right) \tag{9}$$

where, w = the width of a sweep,

β = The angle of soil failure surface,

h = the length of a sweep, and

d = the depth of tillage.

Equation 9 is the sweep model for calculating the volume of soil moving. The mass of soil moving is the product of original soil bulk density and the volume calculated with Eq. 9. This model shows that for a sweep the amount of soil moving depends on the dimensions of the tool, the depth of tillage, and the soil failure angle β. If the internal friction angle of soil is ϕ, the soil failure angle (β) is then $\beta = 45° - \phi/2$ (p131, Gill and Berg, 1968).

All above three models are developed for predicting the volume or mass of soil moving, but there were no any parameters related to the length of straw. This indicated that the effect of surface straw on the amount of soil moving was not included in these models. Therefore, predicted amount of moving soil is not related to the straw length.

2.3 Modeling the Amount of Straw Moving

2.3.1 Extended Straw Moving Zone

According to the models developed above, the area on the surface of soil moving zone can be calculated. The conceptual model from the experimental data suggested that the zone of straw moving consisted of the surface area of the soil moving zone plus an extended area. This extended area is a function of straw length and the direction of straw movement. The actual movement of those straw pieces in the extended area is complicated due to the random orientations of straw pieces, and the friction exists among straw pieces and soil and so on. To simplify the model of straw moving, the contact between the front edge of the soil moving zone and straw is assumed as frictionless; thus, the straw displacement in the extended area is in the normal direction of the front edge of the soil moving zone. Only forward component in the extended moving zone is transported by the tool. Thus, the forward component in the extended area forms the extended straw moving zone. The normal dimension is one length of straw. As a result, the extended dimension of the extended area is:

$$d_{forward} = l \cos\eta \qquad (10)$$

where l is straw length and the angle η of the sweep is shown in Figs. 1 and 5.

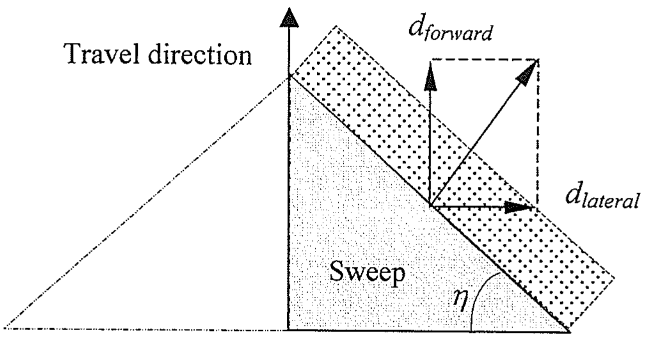


Figure 5. Assumption of extended area of straw moving zone

2.3.2 McKyes and Ali's Model

Equation 10 is for determining the size of the extended area according to the geometry of the front edge of a soil-moving zone. When using McKyes and Ali's model, the surface area of the soil-moving zone was shown in Fig. 3. The geometry of the extended area of straw moving is shown in Fig. 6(a). The mass of straw in its moving zone is the product of straw density and the moving area A. Hence, the mathematical model of straw moving can be written as:

$$A = (r + l)w + r^2\theta + 2rl\sin\theta + \frac{1}{4}l^2(\sin 2\theta + 2\theta) \tag{11}$$

where angle θ is defined by Eq. 5, and r is calculated by Eq. 1.

2.3.3 Two Dimensional Model

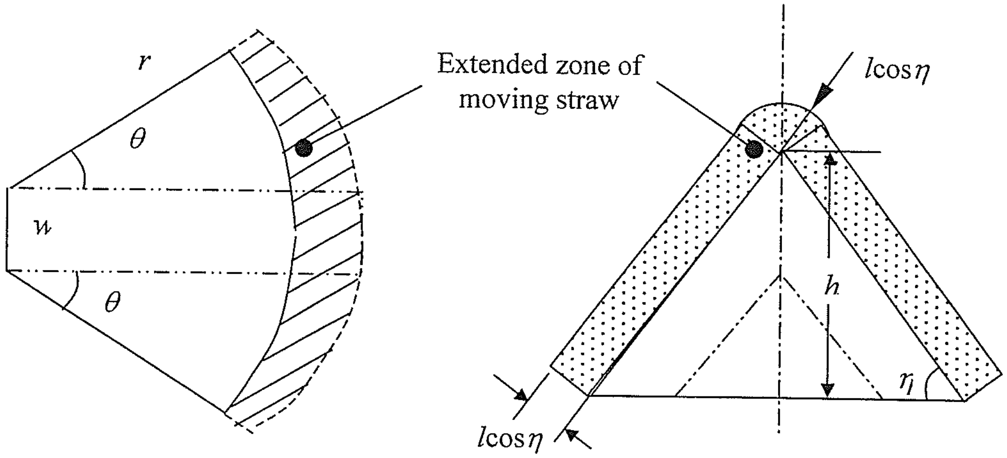
For the two-dimensional model as shown in Fig. 4, the surface area of soil moving zone is a rectangular. Its area is the length of AC times the tool width plus an extended area. The extended area was simplified as a rectangular with the length of one straw length as the front edge of this soil failure zone is a straight line perpendicular to the travel direction. The soil failure angle β is determined by differentiating Eq. 7. Therefore, the area of straw moving zone is:

$$A = [d(\cot\alpha + \cot\beta) + l]w \tag{12}$$

2.3.4 The Sweep Model

When using the sweep model proposed in Section 2.2.3, the moving zone including the extended area of straw as shown in Fig. 6*b*. The total area (A_S) of moving straw is:

$$A_s = \frac{h}{2}\left(w + \frac{d\sqrt{w^2+4h^2}}{2h\tan\beta} \right) + 2l\sqrt{h^2+w^2}\cos\eta + \frac{1}{4}\pi\, l^2 \cos^2\eta \qquad (13)$$



(*a*) (*b*)

Figure 6. Geometry of straw moving zone

(*a*) McKyes and Ali's model (*b*) the sweep model

Equation 13 is derived from the sweep model of the amount of soil moving. It is specifically for sweep tools. Compared with other models, two more geometric parameters of the tool, h and η, are included in this model. The area of straw moving in all of these models is related to the straw length through the extended moving area.

3 PREDICTION OF SOIL AND STRAW MOVING

3.1 Determination of Model Parameters

The 325-mm-wide sweep and the soil conditions in the observational experiment (Section 2.1) were used to calculate the amount of soil and straw moving with the models developed above. The configuration the geometric parameters of the tool were provided including width (w), length (h), rake angle (α), and wing angle (η) as shown in Fig. 1. The tillage depth (d) was 100 mm.

The internal friction angle (ϕ) of this soil is 30°, which was determined with the angle of repose of oven-dried soil. The average bulk density and moisture content over this experiment were 905 kg/m^3 (dry mass) and 21.6% respectively. Methods of determining soil failure angle (β) are different for these two models. For the sweep model, the friction between soil and tool was not considered. Hence, it is determined by the relationship: $\beta = 45° - \phi/2$, 30°.

For McKyes and Ali's model, the soil failure angle is determined by differential equation $dN_\gamma / d\beta = 0$. The definition of N_γ depends on whether the tool is wide or narrow. For a narrow tool, N_γ is defined by Eq. 5. Then β is 53° for ϕ = 30°, and the frictional angle (δ) between soil and the tool is 20° (McKyes, 1985). When the tool is treated as wide, using Eq. 7 to determine the angle β, which is 27.5° under the same conditions.

3.2 Results of Prediction

3.2.1 Amount of Moving Soil

This sweep (325 mm wide) was a wide tool due to the tillage depth was 100 mm. Thus, the two-dimensional model is used to calculate volume of soil moving, which is 0.0108 m^3. When using McKyes and Ali's model, which is for narrow tools, the calculation of the amount of moving soil is then 0.0142 m^3, which is 31% greater than that calculated with the two-dimensional model. For the sweep model, the volume of moving soil is 0.0114m^3. The unit mass of the wet soil in test region was measured and used to calculate the volume of soil moved. The average unit mass was 1100 kg/m^3. All these results were listed in Table 1.

3.2.2 Amount of Moving Straw

The models of straw moving zone (Eqs. 12 and 13) are related to the length of straw. The area of straw moving zone can be calculated using those parameters determined above, and the results are listed in Table 2. The results indicated that the sweep model predicted much smaller moving area of straw than McKyes and Ali's model no matter whether the tool was treated as narrow or wide.

4 MODEL VALIDATION

To validate the predicted results, an experiment was conducted in the soil bin with the same tool as described in Section 2.1. Soil conditions were kept constant. Three different lengths of oat straw were used to study the amount of soil and straw moving, and the relationship between straw length and the amount of straw moving. The experiment was designed to examine the effect of straw length on the amount of moving soil as well.

4.1 Materials and Methods

4.1.1 Experimental Conditions

Oat straw was collected from a field, and then cut it into 100, 175, and 250 mm lengths and stored separately. Each length of straw formed one plot (one treatment), and there were three treatments. Each treatment was replicated three times. Therefore, there were nine test runs. Plots were arranged in random order. For each length, the same mass of straw was manually applied to each plot, and laid flat on the soil surface. The dimensions of a plot were 0.9 m wide and 1.5 m long. Plot length was slightly adjusted due to manually spreading of straw, and the straw density of each plot was recorded according to the actual plot dimensions.

Every plot was tilled once with a single tool of 325-mm-wide sweep. The tool centre was along the centre of a plot over its length in the direction of tool travel. The tillage was operated at the depth of 100 mm and the speed of 5 km/h, and these operational conditions were kept as constant for all test runs.

4.1.2 Soil Preparation

A full width rotary tiller mounted on the soil bin was used for tilling through the width and length of the soil bin to loosen and uniformly mix the soil. To maintain the desired moisture content, water could be sprayed over the bin as necessary. To mix soil uniformly after spraying with water, soil was tilled again 24 h later using the rotary tiller. Then, an iron plate mounted on the rear tool bar of the carriage was used for leveling the soil. Finally, a plain roller mounted on the rear tool bar was used to pack the soil for several times to reach the desired bulk density.

4.1.3 Method of Measuring the Amount of Soil and Straw Moving

When soil was ready, straw was uniformly spread over the soil surface to form a plot. A rectangular hole, which was 0.9 m wide by 1.5 m long by 0.12 m deep, was then dug in the front of the plot before tillage operation (Fig. 7). The bottom of this hole was covered with a piece of plastic sheet. Three soil samples were taken within each plot to measure the unit weight of soil, and monitor soil moisture content and bulk density. The soil and straw moved in this hole were considered as the quantities of soil and straw moving.

After tillage operation, the soil and straw moved in the hole were collected separately and weighted immediately.

The mass of soil and straw moving was directly measured, and the volume of soil moving was calculated according to the unit weight of the soil before tillage. The area of straw moving zone was calculated using the straw density before tillage operation.

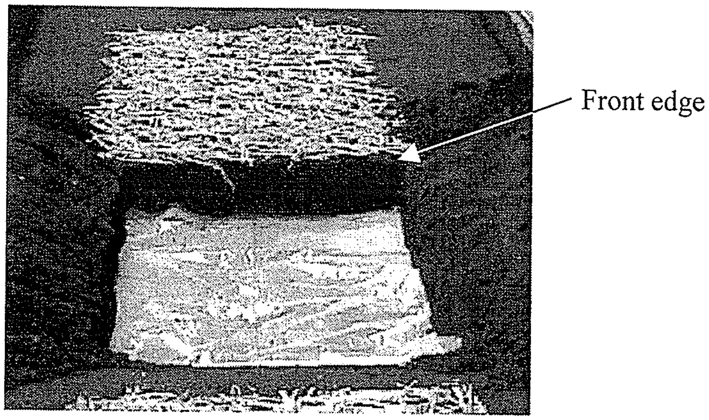


Figure 7. A hole in front of a plot to measure the quantities of soil and straw moving

4.2 Results and Discussion

4.2.1 Amount of Soil Moving

The measured mass and volume of soil moving is listed in Table 2. The average volume of soil moving over three replications does not significantly differ for three lengths of straw. It could be concluded that the straw length does not significantly affect the amount of soil moving for the straw amount applied in this study. Therefore, the assumption in the modeling was verified that the surface straw did not affect the amount of soil moving. The fluctuation of experimental results was mainly caused by the non-uniformity of soil bulk density. Overall average volume of soil moving for the three lengths of straw was 0.0146 m^3, and the volume of soil moving predicted by the two-dimensional model was 0.0108 m^3 with relative error of 26% when the tool was treated as wide. If the tool is narrow and using McKyes and Ali's model, the predicted result is then 0.0142 m^3 with a relative error of 10%. For the sweep model, however, the predicted volume of moving soil is 0.0114 m^3, and the relative error is 22%.

The results of validation indicated that McKyes and Ali's model had the best resolution in predicting the amount of soil moving than the others, even though the aspect ratio of 0.3 does not suggest a narrow tool. The sweep model is better than the two-dimensional model. This conclusion needs to be further verified.

4.2.2 Amount of Straw Moving

Measured areas of the straw moving zone for the three lengths of straw were also summarized in Table 2, where the straw amount of each plot was also provided. The results showed that the area of the straw moving zone increases with increasing straw length, and the moving area of 250-mm-long straw is significantly larger than others. Compared to the predicted results, the sweep model can predict the quantities of straw moving with relative error of 12% and less in the range of straw lengths used in this experiment; but for McKyes and Ali's model, the minimum relative error of predicting the quantities of straw moving is 30%. This validated that the sweep model gives better results when compared to the experimental results than the other models for predicting both the quantities of moving soil and straw.

4.2.3 Discussion

The sweep model was developed for the sweep type of tools. The specific value of this kind of tool is the small rake angle. For other type of tools having larger rake angle, McKyes and Ali's model may be more suitable than the sweep model. The reason that

McKyes and Ali's model is not suitable for predicting the amount of moving soil and straw is the small rake angle of the sweep and the actual length of the tool, as shown in Fig. 8. For McKyes' model, the 'tool length' is supposed to be represented as the dotted line shown in Fig. 8. The portion of the soil behind the rear edge of the tool is referred to as tail region, which does not exist in the real process of tillage operation. This is the reason that the McKyes and Ali's model overestimated the area of the straw moving zone. Besides, it could be a coincidence that the volume predicted by this model is very close to the experimental result when the tool was treated as a narrow tool.

It should be mentioned that experimental results in this study might overestimate the quantities of moving soil and straw. This overestimation could be caused by the measurement method used in the experiment, that is the open hole to measure the amount of moving soil and straw. Soil collapse could happen in the front edge of the hole when a tool passes it, which could cause more soil to enter the hole. However, there was no apparent collapse on the front edge after the tool passed, as shown in Fig. 9. The sharp change of media in the tool path could change the movement of soil and straw. This is a possible reason of experimental error.

Table 1. Predicted and measured volume (m^3) of moving soil

Straw length (mm)	Two-dimensional model	McKyes and Ali's model	The sweep model	Measured *
100	0.0108	0.0142	0.0114	0.0144*a*
175	0.0108	0.0142	0.0114	0.0151*a*
250	0.0108	0.0142	0.0114	0.0144*a*

*The numbers followed by the same letters in the last column show that no significant differences were detected by Duncan test at significant level of 0.05.

Table 2. Predicted and measured areas (m^2) of straw moving zone

Straw length (mm)	Two-dimensional model	McKyes and Ali's model	The sweep model	Measured*
100	0.248	0.429	0.109	0.1230*b*
175	0.272	0.504	0.144	0.1450*b*
250	0.297	0.586	0.181	0.2070*a*

*The numbers followed by the same letters in the last column show that no significant differences were detected by Duncan test at significant level of 0.05.

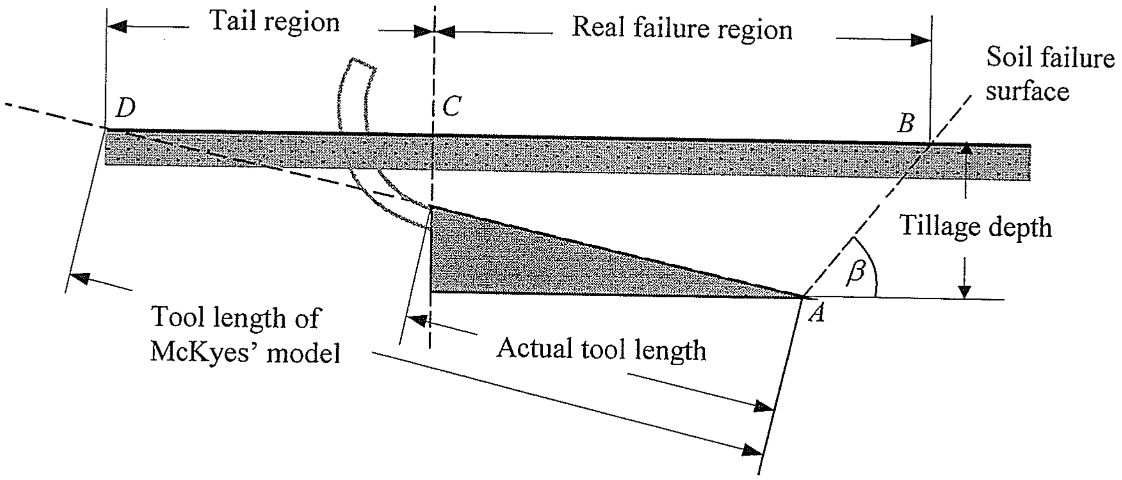


Figure 8. Soil failure regions using McKyes and Ali's three-dimensional model

Figure 9. Soil and straw moved in the hole after tillage operation at the speed of 5 km/h and the depth of 100 mm

5 CONCLUSIONS

Steady-state models of soil and straw movement during tillage with a single sweep were developed and validated by a soil bin experiment. McKyes and Ali's model and a two-dimensional model were applied to the steady-state movement of soil and straw, and then a sweep model was proposed.

For the tillage depth of 100 mm used in this study, the 325-mm-wide sweep was a wide tool. However, McKyes and Ali's model would predict the amount of soil moving, and its accuracy was better than others; but, the amount of straw moving was overestimated 50% and greater than the experimental results. The two-dimensional model had minimum relative error of 43% in predicting the area of straw moving. The accuracy of McKyes and Ali's model in predicting the amount of soil moving could be a coincidence due to modeling error.

The sweep model proposed in this study would predict the amount of moving soil with relative error of 22% and less. In prediction of straw moving area, the maximum relative error of the sweep model was only 12%. This sweep model, however, is specially developed and validated for sweep tools. Further study is required to develop suitable models for other type of tools.

6 REFERENCES

Gill, W. R. and G. E. V. Berg, 1968. *Soil dynamics in tillage and traction.* Agriculture Research Service. Washington D. C., Department of Agriculture, US.

Govers, G., K. Vandaele, P. J. J. Desmet, J. Poesen, and K. Bunte. 1994. The role of tillage in soil redistribution on hillslopes. *European Journal of Soil Science* 45: 469-478.

Koolen, A. J., and H. Kuipers. 1983. *Agricultural Soil Mechanics*. New York, NY: Springer-Verlag.

Lindstrom, M. J., J. A. Schumacher, and T. E. Schumacher. 2000. TEP: a tillage erosion prediction model to calculate soil translocation rates from tillage. *Journal of Soil and Water Conservation*. 55(1): 105-108.

Liu, J., R. L. Kushwaha, D. A. Lobb and Y. Chen 2004. Steady-state models for the movement of soil and straw during tillage. 2004 CIGR International Conference, Beijing, China

Lobb, D. A., R. G. Kachanoski, and M. H. Miller. 1995. Tillage tranlocation and tillage erosion on shoulder slope landscape positions measured using Cs-137 as a trace. *Canadian Journal of Soil Science*. 75:211-218.

Lobb, D. A. and R. G. Kachanoski. 1999. Modelling tillage erosion on the topographically complex landscapes of southwestern Ontario. *Soil and Tillage Research*. 51: 261-277.

McKyes, E. 1985. *Soil cutting and tillage*. Elsevier Science Publishing Company Inc. 52 Vanderbilt Avenue, New York, NY10017, U.S.A

McKyes, E. and O. S. Ali. 1977. The cutting of soil by narrow blades. *Journal of Terramechanics*. 14(2): 43-58.

Sharifat, K. 1999. *Soil translocation with tillage tools*. Unpublished Ph.D. thesis. Saskatoon, SK: Dept. of Ag. and Bioresource Eng., University of Saskatchewan.

CHAPTER 4

Modeling of Soil Movement by Tillage with a Single Sweep

ABSTRACT

A three-dimensional model was developed to predict the soil displacement by a single 325-mm-wide sweep. Soil displacement by a sweep was simplified into three phases: forced, projectile, and rolling displacement based on an observational experiment in a soil bin. Tillage tool geometric parameters, soil properties, and tool operational parameters were physically involved in the model. The operational parameters were tillage depth and speed. The model was validated using the data obtained from a soil bin and field experiment, and the results indicated that the model was effective in predicting both forward and lateral displacement of soil by a single sweep. The effect of straw and standing stubble on soil displacement was expressed as including or excluding the component of rolling displacement in total displacement. The effect of shank on soil and straw movement was not included in this model. The primary advantages of this model are its ease of calculating, and its parameters are easily determined. Predicted soil displacement has 19% and lower relative error compared to the experimental results.

1 INTRODUCTION

Soil movement always accompanies tillage practices. Quantitatively describing the amount and distance of soil being relocated by a tool is very important for both managing tillage practices and designing new tools for variety of purposes to reduce soil erosion and energy requirements. Steady-state models describing the amount of soil moving has been studied (Liu et al., 2004).

Regarding the study of soil displacement, Soehne (1956) simplified the interaction of a cutting tool and soil into a two-dimensional segment model (Fig. 1), which was described by Gill and Berg (1968). The absolute velocity (shearing velocity, Eq. 1) of a soil segment is a function of tool travel velocity (V_0), rake angle (α), and soil failure angle (the angle of passive failure surface, $\beta = 45° - \phi/2$ where ϕ is soil internal friction angle). However, it has not been used and verified.

$$V_s = V_0 \frac{\sin\alpha}{\sin(\alpha+\beta)} \tag{1}$$

In the study of tillage translocation, researchers defined the linear or non-linear equations for calculating one-dimensional soil displacement, such as relations of translocation and slope gradient (Lindstrom et al., 1992; Govers et al., 1994) and tillage translocation (Lobb et al., 1995; Lobb and Kachanoski, 1999; De Alba, 2001). Whatever the formats of these models, they are stochastic representations of soil movement rather than physically based equations. The effect of tillage depth and tillage speed is implicitly represented. Sharifat (1999) developed a soil movement model according to the stress distribution in the soil in front of a tool. The influences of soil properties were treated as independent variables, and were involved into the model through regression analysis. Rahman (2004) studied soil movement using point tracers in a soil bin at the speed range of 1 to 5 km/h; but only regression relations of soil displacement were proposed.

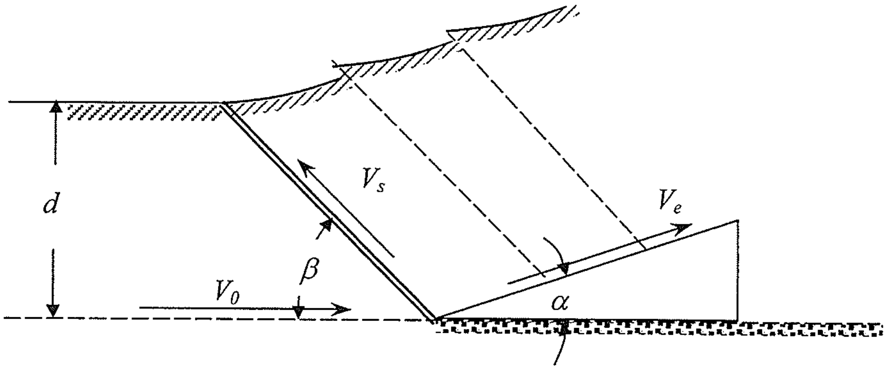


Figure 1. Geometric relations between velocities and lengths for a segment of soil reacting to an inclined tillage tool (Gill and Berg, 1968)

Torri and Borselli (2002) studied the soil movement by a moldboard plow, and the soil movement was simplified to three phases including drag, jump, and rolling. Mathematical models for each phase were physically established. However, the motion analysis of soil was based on a single point on the tool surface, this resulted in (1) the depth of tillage operation being neglected and (2) the rotational motion of soil blocks also being neglected. Besides, the rolling phase was separately studied and was treated as an important phase since the study was for the purpose of tillage erosion. On a plane field, soil rolling could be stopped by standing stubble. Moreover, the effect of crop residue on soil movement was not considered.

Unfortunately, knowledge of understanding the process of soil and crop residue interaction during tillage is not currently available; it lacks physically based models to describe soil movement for a variety of purposes, such as designing new tillage tools.

The objectives of this study were:

a. To develop a mathematical model to describe the soil displacement by a single sweep based on the physical process of soil and tool interaction;

b. To incorporate the effect of crop residue on soil movement into the soil displacement model; and,

c. To validate the model by a soil bin and a field experiments.

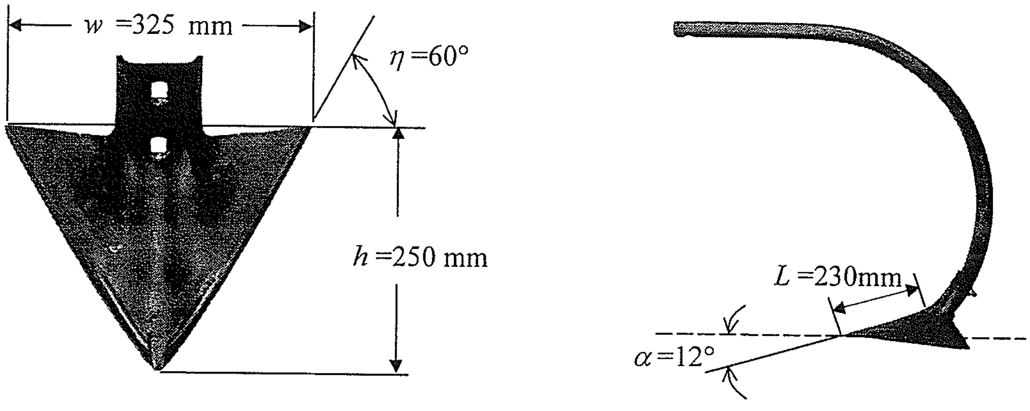
2 MODEL DEVELOPMENT

2.1 Experimental Examination of Soil Movement

2.1.1 Experimental Conditions

The observation of soil movement was conducted in an indoor soil bin, which is located at the University of Manitoba, Canada. The dimensions of the bin are 15 m long and 1.75 m wide. Two rails on each side of the bin support a tool carriage, which is powered by a 7.46 kW electric motor equipped with speed control. The bin is 0.5 m deep, and is filled with loamy sand soil to a depth of 0.4 m. The average moisture content of the bin soil was 16.3% with standard deviation of 1.2%, and the average bulk density was 1220 kg/m^3 with standard deviation of 53 kg/m^3 over the entire experiment.

To observe the effect of crop residue on soil movement, straw was manually applied and laid flat on the soil surface to represent surface crop residue. Oat straw was used because cereal is a popular crop in Canadian prairies provinces, where sweep type of tool is one of common tools. Therefore, a 325-mm-wide sweep was selected as a tillage tool (Fig. 2).



(a) (b)

Figure 2. (*a*) The sweep (McKay 50-12K) and (*b*) the sweep with the shank used in the experiment

To observe the lateral (perpendicular to the direction of tool travel) and longitudinal (the direction of tool travel) movement, two video cameras were mounted on the tillage implement during tillage. One was located at the centre of the front tool beam, and faced to the tool; the other was located at the side of the tool. The analysis of these motion pictures provided an optical means of characterizing tool–soil–straw interaction.

2.1.2 Soil Movement

Tillage speed and the geometry of the tool control the pattern of soil movement. Soil mass on the surface of the tool consisted of a number of soil blocks as shown in Fig. 3. A moving zone of soil in the front of tool was observed. According to the observation, the interaction between soil and the tool was simplified into four stages as follows:

- Stage 1: soil was cut and failed; soil blocks were formed;
- Stage 2: failed soil was forced to slide along the tool surface;
- Stage 3: soil blocks reached the rear edge of tool, and were projected away;

- Stage 4: soil blocks landed on the ground. Rolling, sliding or breaking occurred.

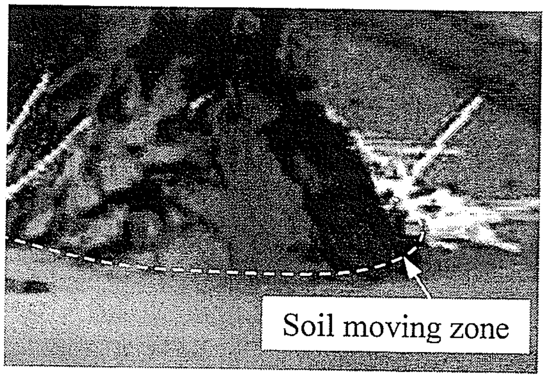


Figure 3. Soil blocks moving on the surface of the sweep

Soil movement in the stage 1 was neglected in the following analysis. The actual motion of soil blocks depended on tool operating speed. Once the kinetic energy acquired by a soil block was high enough to overcome its gravity, the block would be projected. Otherwise, the block could fall or topple to the ground. The observation proved that most soil blocks fell back down to the furrow if the tillage speed was very low.

2.1.3 Effect of Straw on Soil Movement

Moving soil causes straw movement. All the forces acted on the straw made straw stay on the soil surface, and move together with the soil blocks. The forward component of projectile motion pushes straw moving forward. The important action during soil and straw interaction is the rotation of soil clod and the overturning of straw. The rotation of soil clods causes the overturning of straw. Soil blocks could rotate more than once, but straw could only overturn once. Soil was distributed to a wider area on no-straw surface than on the surface covered with straw. Straw could reduce soil displacement by reducing rolling phase of soil movement.

2.2 Modeling Soil Displacement

2.2.1 Simplification of Soil Movement

The pattern of soil movement depends on the tool geometry, operating depth and speed, and soil conditions. To develop the model of soil movement, the following assumptions were made.

- The soil lifted by a tool is considered as consisting of a number of soil blocks as shown in Fig. 1, which can slide past each other;
- Soil is uniform, and its bulk density is constant before and after failure;
- Soil is uniform and has perfect-rigid-plasticity property;
- The effect of tillage speed on the failure geometry is neglected; and,
- The air resistance on the soil is neglected.

With these assumptions, the movement of a soil block can be described as follows: as it is lifted by tillage tool, the geometric relocation of soil on the tool causes horizontal displacement. At the moment leaving the tool surface, the soil block is thrown away at their instantaneous velocities. When the soil block lands on the ground, it may roll, which also contributes to total soil displacement. The resultant displacement of the mass centre of any soil block is a combination of following phases:

a) Forced displacement (S_F). Dotted lines in Fig. 4 show the simplified process of forced displacement: a soil block is cut and failed along its failure angle (β), and then lifted onto the tool (transitional motion); a rotational motion occurred simultaneously. Both transitional and rotational motion causes displacement, and it is named forced displacement.

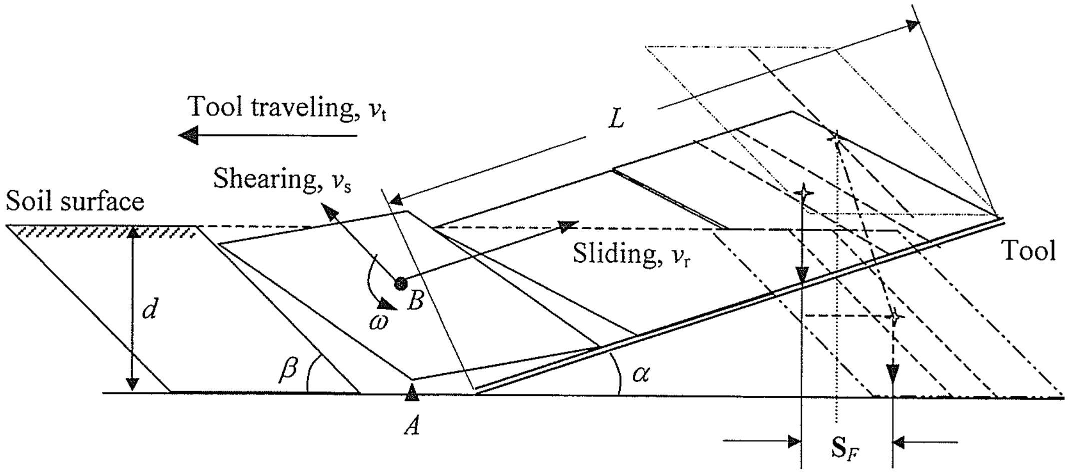


Figure 4. Block model and forced displacement of soil during tillage

b) Projectile displacement (S_P). While the tool moving forward, the soil blocks slide along the tool surface and then they are projected when arriving the rear edge of the tool. This phase of movement is referred to as projectile displacement.

c) Rolling and sliding displacement (S_R). The first two phases of soil displacement result from the direct interaction between tillage tool and the soil. At the end of projectile process, soil blocks land on the ground at velocities of horizontal components of the projectile velocity. This becomes the initial movement of rolling and sliding. The displacement is called rolling and sliding displacement.

The soil displacement during tillage can be represented as a vector summation of all three phases (Eq. 2). Each phase of soil displacement will be discussed in following sections.

$$\mathbf{S} = \mathbf{S}_F + \mathbf{S}_P + \mathbf{S}_R \tag{2}$$

A sweep (Fig. 2) was selected as a tillage tool in this study, and it is simplified into a simple shape *ABCG* and placed in a Cartesian coordinates as shown in Fig. 5. The simplified tool *ABCG* is symmetrical, and each side of the tool is a flat surface. The direction of *X* represents the direction of tool travel or forward movement, *Y* represents the direction of lateral movement, and *Z* represents vertical movement. A soil block reaches the tool from point *C*, and then slides along tool surface to point *P* and is projected. If V_B represents the projectile velocity, there are two components in the plane perpendicular to plane *ABC*: the "vertical" component in this plane $V_B \sin(\beta - \alpha)$ and the horizontal component (forward projectile velocity).

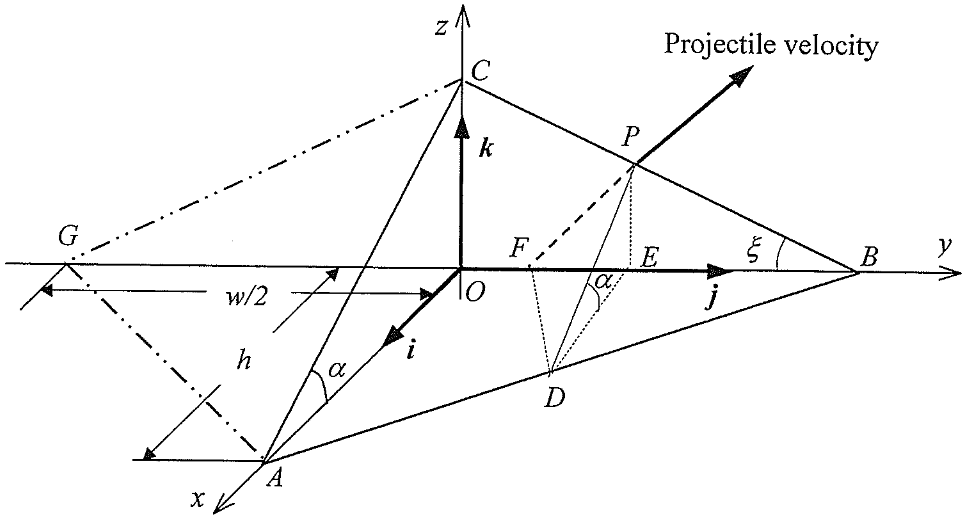


Figure 5. Motion vector of a soil block on the surface of the sweep

2.2.2 Forced Displacement ($\mathbf{S}_F$*)*

The three-dimensional displacement $\mathbf{S}_F$ can be written as:

$$\overline{S}_F = S_{FX}\mathbf{i} + S_{FY}\mathbf{j} + S_{FZ}\mathbf{k} \tag{3}$$

The forced displacement of a soil block includes two components: plane transitional and angular displacement as shown in Fig. 4. Two components of horizontal forced displacement are the forward $S_{FX} = \Delta x$ and lateral $S_{FY} = \Delta y$ displacement respectively.

Using the central point on the rear edge (BC in Fig. 5) of the tool to represent the average displacement of soil, then two horizontal components of forced displacement in the three-dimensional coordinates (Fig. 5) are:

$$\begin{cases} S_{FX} = d\dfrac{\cos(\beta-\alpha)-\cos\beta}{2\sin\beta}+\dfrac{L}{2}(1-\cos\alpha) \\ S_{FY} = d\dfrac{\cos(\beta-\xi)-\cos\beta}{2\sin\beta}+\dfrac{w}{4}(1-\cos\xi) \end{cases} \tag{4}$$

Where, w = tool width,

d = tillage depth,

ξ = inclined angle of tillage tool to y-axis, Fig. 5

α = tool rake angle (inclined angle of the tool to x-axis), and

L = the distance on the tool surface from the front to the rear edge (Fig. 4).

2.2.3 Projectile Velocity and Its Direction

Equation 1 has not been used and verified. A preliminary study of projectile velocity had been carried out using the experimental data conducted in a soil bin, and the results showed that the displacement of soil block would have 50-100% or even more relative error when using Eq. 1 as a projectile velocity. The reason is that the soil blocks do not rotate during projection if this equation was used to describe soil movement. The rotation of soil block had been observed in the experiment. All of these facts indicate that Eq. 1 would not represent the real movement of soil blocks during tillage.

After the first stage of soil and tool interaction, the soil blocks rotate an angle of α (rake angle) and slide along the surface of the tool. Figure 4 shows the process of a soil block sliding on a tool. According to the principle of the general motion of a rigid body in space (Beer and Johnston, 1977) the absolute velocity at the mass centre (B) of a soil block is the resultant of shearing velocity V_A at point A and the relative velocity $V_{B/A}$:

$$V_B = V_A + V_{B/A} \tag{5}$$

The soil block is projected with the velocity of V_B if it gained enough kinetic energy to overcome the potential energy of gravity. The velocity V_A at the base point A is equal to the shearing velocity (v_s), which is directed at the angle β to the horizon and calculated by Equation 1. The shearing velocity (v_s) is the sum of the following two velocities:

a) The travel velocity of the tool (v_t), which is the drag motion; and

b) The sliding velocity (v_r), which is the velocity of soil block relative to the tool and directed along the tool surface. It is a relative motion.

According to the principles of kinematics, these three velocities v_s, v_t, and v_r must form a closed hodograph as shown in Fig. 6. The vector sum of the tillage velocity and the sliding velocity is equal to the shear velocity. Tool travel, soil block sliding and shear velocities are given by the following relationships in a Cartesian coordinates:

$$\bar{v}_s = \bar{v}_t + \bar{v}_r \tag{6}$$

$$v_s \sin(\beta - \alpha) = v_r \sin\alpha \tag{7}$$

$$-v_s \cos(\beta - \alpha) = -v_t + v_r \cos\alpha \tag{8}$$

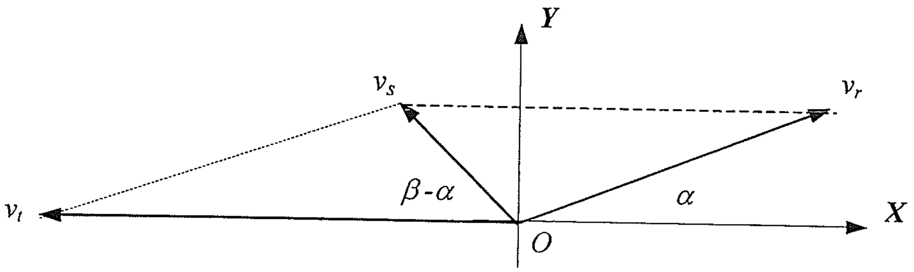


Figure 6. Hodograph for the interaction of soil and tillage tool

Then the equations for calculating the velocities of soil block are:

$$v_r = v_t \frac{\sin(\beta - \alpha)}{\sin \beta} \tag{9}$$

$$V_A = v_s = v_t \frac{\sin \alpha}{\sin \beta} \tag{10}$$

where, $\alpha =$ rake angle of the tool,

$\phi =$ internal friction angle of soil.

The velocity $V_{B/A}$ can be written as:

$$V_{B/A} = \omega r_{B/A} \tag{11}$$

Assuming soil blocks are the same squares with the edge length of a, and all squares rotate the same angle (the incline angle of the tool) in the same time. Then $\omega = (\alpha/a)v_t$ and $r_{B/A} = \sqrt{2}a/2$. The velocity $V_{B/A}$ is then:

$$V_{B/A} = \frac{\sqrt{2}}{2}\alpha v_t \tag{12}$$

Defining V_B as the projectile velocity, then:

$$V_B = \frac{\sin \alpha}{\sin \beta} v_t + \frac{\sqrt{2}}{2}\alpha v_t \tag{13}$$

As shown in Fig. 5, the projectile velocity V_B is related to the speed of tool operation. The projectile direction depends on the angle of soil failure and the incline angles of the tool. Assuming the angle of soil failure in lateral direction is also equal to β, the process shown in Fig. 4 happens in the plane *DFP* of Fig. 5, which is perpendicular to the tool surface *ABC*. The velocity V_B can be resolved as a horizontal component $V_B \cos(\beta - \alpha)$ in *x-y* plane (v_x) and a "vertical" component $V_B \sin(\beta - \alpha)$ parallel to the *y–z* plane. The component of $V_B \sin(\beta - \alpha)$ rotates an angle of ξ while the soil block slides on the tool surface. The component of projectile velocity in *y–z* plane (V_B^y) is calculated as the same principle as Eq. 13. The velocity V_B^y forms an angle of (β–ξ) to the horizontal direction, which will be resolved as a lateral velocity v_y and a vertical velocity v_z. As a result, three components of projectile velocity in the Cartesian coordinates are:

$$\begin{cases} v_x = V_B \cos(\beta - \alpha) \\ v_y = V_B^y \cos(\beta - \xi) \\ v_z = V_B^y \sin(\beta - \xi) \end{cases} \tag{14}$$

$$V_B = \frac{\sin\alpha}{\sin\beta} v_t + \frac{\sqrt{2}}{2} \alpha v_t \tag{15}$$

$$V_B^y = V_B \sin(\beta - \alpha) + \frac{\sqrt{2}}{2} \xi v_t \tag{16}$$

2.2.4 Projectile Displacement (S_P)

If a soil block is projected from a point (x_0, y_0, z_0), its trajectory in the plane of $x - z$ can be described by following equations:

$$\begin{cases} x = x_0 + v_x t \\ z = z_0 + v_z t - \frac{1}{2} g t^2 \end{cases} \tag{17}$$

Using the principle of mechanical energy conservation during the projection, then the projectile time *t* is:

$$t = \frac{\sqrt{v_z^2 + 2 z_0 g} + v_z}{g} \tag{18}$$

Substituting Eq.18 into Eq.17, the landing location of a soil block can be derived as:

$$\begin{cases} x = x_0 + \dfrac{v_x}{g}\left(\sqrt{v_z^2 + 2z_0 g} + v_z\right) \\ y = y_0 + \dfrac{v_y}{g}\left(\sqrt{v_z^2 + 2z_0 g} + v_z\right) \\ \\ v_x = V_B \cos(\beta - \alpha) \\ v_y = V_B^y \cos(\beta - \xi) \\ v_z = V_B^y \sin(\beta - \xi) \end{cases} \tag{19}$$

Equation 17 is for calculating new locations after projection. Coordinate x represents the direction of tool travel, which is referred to as forward displacement hereafter. Coordinate y represents lateral movement. At the end of projection, soil blocks land on the ground. The landing position depends on the original location of the soil block on the tool before it is projected. The landing points on both sides of the tool are assumed as symmetrical, and all the points (e.g. O, C, and E) on both sides are linearly distributed (Fig. 7). Thus, the average forward displacement could be calculated using the centre point $c(x_c^0,\ y_c^0, z_c^0)$ on one side of the tool surface. For example, the average forward displacement caused by projection will be:

$$S_{PX} = \frac{1}{3}(x_c - x_c^0) \tag{20}$$

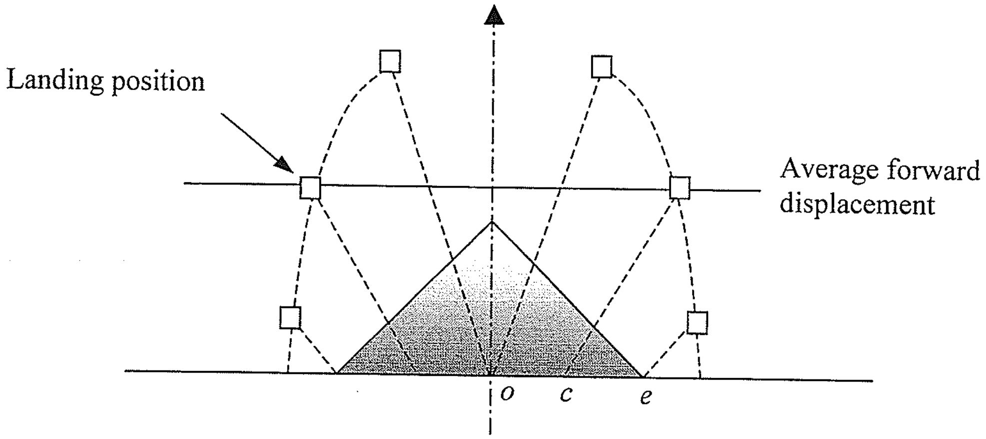


Figure 7. Soil projectile movement

2.2.5 Rolling and Sliding Displacement

At the end of projection, soil blocks are dropped on the ground and then start rolling and sliding process. Soil blocks are treated as a system of particles, and this system is moving on the soil surface while soil blocks are rolling and sliding in the system. To simplify the analysis, this moving process is considered as a sliding of this particle system as shown in Fig. 8.

The frictional coefficient between the system and the soil surface is assumed as $\mu = \tan(\delta)$, where δ is the frictional angle of soil blocks on the soil surface. The deceleration of the particle system is then:

$$a = -\mu g \tag{22}$$

The sliding displacement is:

$$S = \frac{V_0^2}{2\mu g} \tag{23}$$

where, V_0 is the horizontal component of projectile velocity at the end of projection.

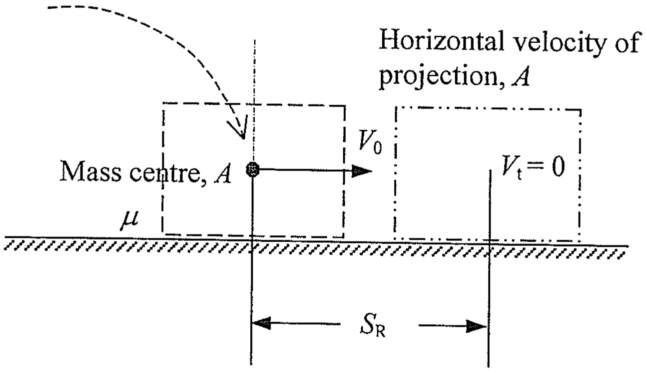


Figure 8. The sliding process of a system of soil blocks

The forward and lateral displacement can be calculated according to two horizontal components of projection. Hence, forward and lateral components are:

$$\begin{cases} S_{RX} = \dfrac{v_x^2}{2\mu g} \\ S_{RY} = \dfrac{v_y^2}{2\mu g} \end{cases} \tag{24}$$

2.2.6 Effect of Straw on Soil Displacement

It appears that the effect of straw on the soil movement was not included in the model developed above. Actually, this effect is included in deciding rolling and sliding displacement. That is, soil displacement is only consisted of projectile and forced phyases when standing stubble exists due to the rolling/sliding action could be completely stopped by the standing stubble. When only flat straw exists, the frictional coefficient between soil blocks and the straw surface could be different that impacts the displacement of soil sliding/rolling.

3 MODEL APPLICATION

3.1 Coordinate System

The 325-mm-wide sweep was used as an example to calculate soil displacement using the model developed above. The coordinate system is the same as that used in Fig. 5. The dimensions were measured off the tool (Fig. 2), and the coordinates were arranged as shown in Fig. 9. The original point and its horizontal plane represents the plane of the sweep bottom, which is an constant tillage depth below soil surface. Assuming the depth of tillage is 100 mm, then the coordinates of three desinated points (*O, C, and E* shown in

Figures 2 and 10 on the rear edge of the sweep can be indexed. The centre point *C* is used to calculate the average displacement of the soil.

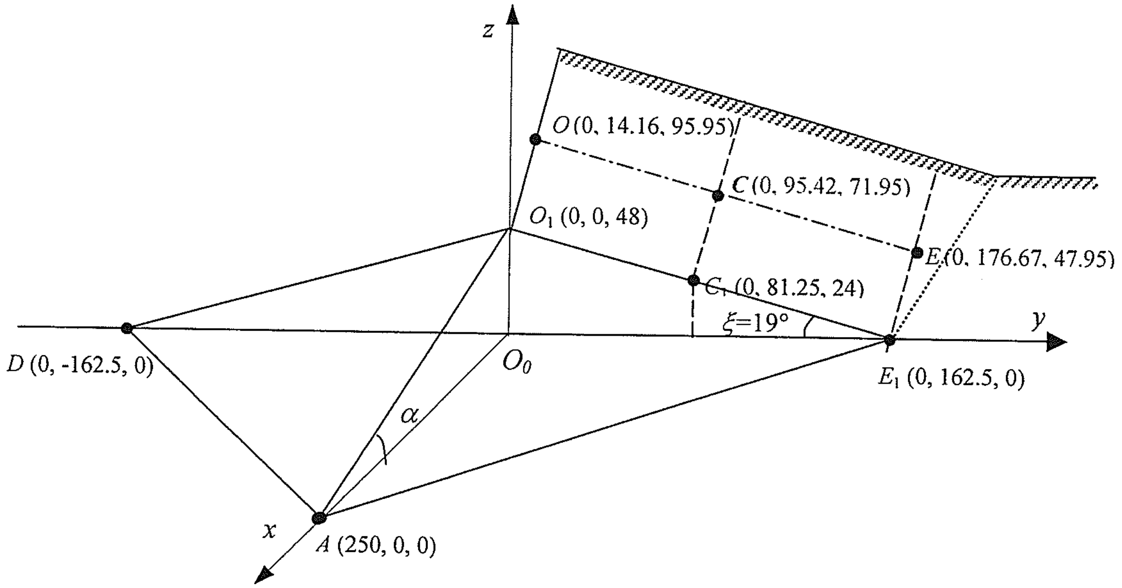


Figure 9. Coordinate system of the sweep for calculating soil displacement (unit: mm)

3.2 Summary of the Model

Equation 2 represents the general soil displacement, which includes three phases of forced, projectile, and rolling displacement. Each phase was mathematically expressed in a three-dimensional coordinate system. The equations for calculating the average forward and lateral displacement of soil movement by a sweep can be summarized as follows.

$$\begin{cases} x_c = x_c^0 + \dfrac{v_x}{g}\left(\sqrt{v_z^2 + 2z_c^0 g} + v_z\right) \\ y_c = y_c^0 + \dfrac{v_y}{g}\left(\sqrt{v_z^2 + 2z_c^0 g} + v_z\right) \\ \\ v_x = V_B \cos(\beta - \alpha) \\ v_y = V_B^y \cos(\beta - \xi) \\ v_z = V_B^y \sin(\beta - \xi) \end{cases} \qquad (23)$$

$$\begin{cases} S_{PX} = \dfrac{1}{3}(x_c - x_c^0) \\ S_{PY} = \dfrac{1}{3}(y_c - y_c^0) \end{cases} \tag{24}$$

$$\begin{cases} S_{FX} = d\dfrac{\cos(\beta-\alpha)-\cos\beta}{2\sin\beta} + \dfrac{L}{2}(1-\cos\alpha) \\ S_{FY} = d\dfrac{\cos(\beta-\xi)-\cos\beta}{2\sin\beta} + \dfrac{w}{4}(1-\cos\xi) \end{cases} \tag{25}$$

$$\begin{cases} S_{RX} = \dfrac{v_x^2}{2\mu g} \\ S_{RY} = \dfrac{v_y^2}{2\mu g} \end{cases} \tag{26}$$

3.3 Model Parameters and the Results of Calculation

Model parameters include tool geometric and soil mechanical parameters. Geometric parameters of the tool required to calculate soil displacement are presented in both Figures 2 and 10. Soil parameters include failure angle (β) and average size (a) of soil blocks after tillage. The soil failure angle can be estimated using the relationship $\beta = 45° - \phi/2$, which is 30° for the internal friction angle of 30°. The blocks are assumed as squares with the dimension of the tillage depth. The results of calculation are listed in Table 1. Calculated results indicate that higher tillage speed causes greater soil displacement by increasing both projectile and sliding/rolling displacement. The rolling diasplacement is also related to the speed of tillage, but it is assumed that the rolling distance of the mass centre of a soil block remains the same in this model; the speed only affects the breakage of soil blocks.

4 MODEL VALIDATION

A soil bin and a field experiments were conducted to develop and validate the model of soil displacement. The soil bin was described in Section 2.1. Oat straw was manually applied and laid flat on the soil surface, and there were no other crop residues in the soil bin. This situation of straw is referred to as flat straw hereafter. The field experiment was designed to verify the model under field conditions. Soils in the bin and the field were the same texture, loamy sand. Tillage tool was a single 325-mm-wide sweep (Fig. 2).

Table 1. Results of predicting the soil displacement by tillage with a 325-mm-wide sweep at three speeds. Soil: loamy sand, bulk density 1220 kg/m^3 and 16% moisture content

Tillage Speed (km/h)	**Phases of displacement** (mm)						**Total displacement** (mm)	
	Forced		Projectile		Rolling			
	Forward	Lateral	Forward	Lateral	Forward	Lateral	Forward	Lateral
5	10	16	99	72	40	26	149	114
7.5	10	16	149	113	90	59	249	188
10	10	16	205	157	160	105	375	278

4.1 Field Conditions

An oat field of 60-m by 100-m, which is located at Carman Research Station, in Manitoba (Canada) was selected as the experimental field. Oat was harvested in middle of August, and the standing stubble of 150 to 180-mm-high was left. Oats were also planted previous year.

Two residue conditions were prepared in the field. Condition 1 was designed to simulate the soil bin conditions. That is, all the crop residues on the soil surface were completely removed beforehand. Then flat straw was manually applied. Condition 2: standing stubble was kept and all other residues were removed, and then flat straw was applied as was done in condition 1. These two field conditions were also designed to study the effect of standing stubble on soil and straw movement.

The moisture content of the field soil was maintained by watering daily, and its average was 18.4% with standard variation of 2.75%. The average bulk density of the field soil was 1330 kg/m^3 with standard deviation of 80 kg/m^3.

4.2 Experimental Design and Measurements

Tillage operating speed and depth were 5 km/h and 100 mm respectively for both the soil bin and the field experiments. Oat straw was cut into 100, 175, and 250-mm-long pieces, and collected separately to use as flat straw. The amount of the flat straw was 0.108 kg/m^2 for both experiments. One bare soil (no flat straw) treatment was added in the soil bin experiment, plus three lengths of straw, there was four soil bin treatments. Three lengths of straw combining two residue conditions formed six field treatments.

The field was divided into six 4-m-wide and 40-m-long blocks perpendicular to the planting rows, and each block contained three plots. Field operation was always perpendicular to the planting rows. The measurement area in each plot had the same width of 0.975 m, which was three times of a tool width, and 1.5 m long. The same design was also applied to the soil bin experiment. As limited length of the soil bin, there were three plots for each tool operation. Thus, the blocks were repeated in the same bin. Both experiments were carried out with three replications of randomized complete blocks.

To extend the data range of model validation while the weather conditions still allowed, field experiment at the speed of 10 km/h was added under residue conditions 1 and 2 for one straw length (175 mm). Two more blocks were arranged beside those blocks for 5 km/h. Plots were also randomly assigned.

Measurements were forward and lateral displacement of soil and straw. The movement of the soil in the central third of a plot was traced using point tracers, which were situated in this area. Point tracers were nine aluminum cubes of 1 cm^3, and they were arranged in a line perpendicular to the travel direction of the tool. These cubes were inserted into the soil, and the top surfaces of them were made even with the soil surface to trace the movement of the surface soil. In every plot, tracers were set up first. Then, straw was manually applied and laid flat on the soil surface. The flat straw covered all tracers.

4.3 Experimental Devices

A tool unit for the field experiment was specially designed and fabricated (Fig. 10). It has four wheels and can be drawn by a tractor through its one point hitch. The inner frame and the outer frame are connected by a parallel four-lever mechanism. There is one hydraulic cylinder on each side of the frame. The hydraulic cylinder, which is operated by a tractor's power take-off, is installed between the inner frame and an arm to adjust the depth of tillage. Tools were mounted on the tool bars of the inner frame.

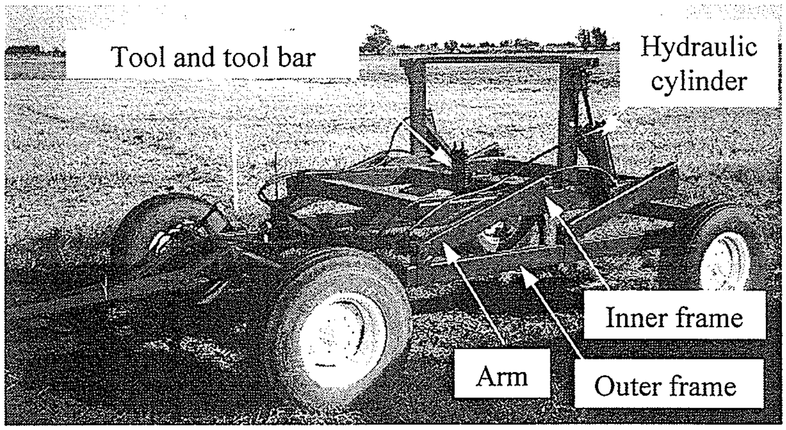


Figure 10. The tool unit for the field experiment

A device, which could freely slide along the rails of the bin, was made for soil bin experiments to set up and measure tracers' positions before and after tillage. A pointer could laterally slide along it. A 2.4-m-long and 1.8-m-wide wooden frame was made, and two 2.4-m-long steel angles were mounted on the side beams to support the device for field experiment. Tape measurers were attached on a steel angle and the measurer to read lateral and longitudinal displacements.

4.4 Results and Discussion

4.4.1 Measured Soil Displacement

Measured value of the average displacement of tracers are listed in Table 2, and the results of statistical analysis are also given for each pair of experiments. For the field condition 1 (flat straw only) and the soil bin condition, both forward and lateral displacement are notably different. Soil displacement is larger under field conditions than that in the soil bin conditions. This is probably caused by higher bulk density of the field soil as well as the influence of roots in the field soil. The roots could resist soil blocks being broken, and then produce larger rolling displacement. Besides, the vibration of the tool unit caused by the uneven field surface was also suspected as a reason of the larger displacement in the field conditions. However, no significant differences were detected between those results from the field and soil bin conditions because of large variance of experimental data. Tool operating speed significantly affects soil displacement. For the field operation, both forward and lateral displacements at speed of 10 km/h are significantly larger than those at 5 km/h, and a doubling in speed produces a doubling in soil displacement. Compared to soil displacement on bare soil, a significant decreasing trend was detected for soil forward displacement at the soil surface with flat straw. The flat straw also numerically reduced lateral soil displacement. Flat straw reduces soil displacement by resisting the rolling phase of soil displacement.

Experimental observation indicated that the variances of measurements for both field and soil bin experiments were caused by non-uniform soil bulk density, tool vibration, and the shank. The shank affects soil movement by hitting soil blocks or tracers.

Table 2. Experimental results of soil displacement after tillage operation with a single 325-mm-wide sweep at different tillage speeds under field and soil bin conditions.

Pairs of experiments			**Displacement** (Standard deviation), mm	
			Forward	Lateral
1	Flat straw only, 5 km/h	Field	195 (35) *a**	112 (17) *a*
		Soil bin	115 (44) *a*	107 (30) *a*
2	Field conditions, flat straw only	5 km/h	195 (35) *a*	115 (15) *a*
		10 km/h	448 (50) *b*	229 (53) *b*
3	Soil bin conditions, 5 km/h	Flat straw	115 (7) *a*	107 (30) *a*
		Bare soil	184 (23) *b*	129 (17) *a*

* The same letter in each pair of experiments indicates that two results in this pair has no significant difference (Duncan test at significant level of 0.1).

4.4.2 Validation of Predicted Soil Displacement

For the sweep used in this study, the model predicted both forward and lateral displacement of soil by comparing the results in tables 1 and 2. Table 3 summarized and listed the relative errors of predicted soil displacement compared to those measured values. The relative error of this model is 19% and less except the forward displacement when flat straw exists under the field operations at the speed of 10 km/h. When stubble and flat straw exists, the speed of 10 km/h caused larger error (33%) of prediction if the rolling and sliding component of soil was eliminated in the predicted forward displacement. Actually, soil blocks rolling/sliding also happened on the straw surface of field soil when the speed of tillage was 10 km/h. This is evident in the video recorded with a video camera mounted at the front of the tool. If the rolling and sliding component was added into the forward displacement, the relative error is reduced to 16%. For the results from soil bin conditions at the speed of 5 km/h, including soil rolling and sliding displacement can predict better results under the bare soil conditions; when flat straw exists, excluding rolling and sliding displacement receives better prediction.

4.4.3 Discussion

To achieve desired effect of tillage practices, soil has to be mechanically moved or disturbed. For example, a certain pattern and quantity of soil movement was needed to bury appropriate percent of crop residue. However, unnecessary soil movement could negatively change the properties of soil, and consume extra energy. To optimize soil movement for the purposes of reducing soil erosion and energy requirements in both designing new tillage tools and managing tillage practices, physical-based mathematical models of soil movement are definitely required. The reason is that soil movement depends on tool parameters, operational parameters, and field conditions. Physical-based mathematical models can connect these parameters. To meet this requirement, a mathematical model of soil movement was physically developed in this study for sweep type of tools.

Table 3. Validation of predicted soil displacement

Experimental conditions	**Displacement**, mm					
	Forward			**Lateral**		
	Measured	Predicted	Relative error (%)	Measured	Predicted	Relative error (%)
Soil bin, bare soil, 5 km/h	184	149	19.0	129	114	11.6
Soil bin, flat straw, 5 km/h	115	109 (no rolling & sliding)	5.2	107	88 (no rolling & sliding)	17.8
Field, Stubble and flat straw, 10 km/h	323	215 (no rolling & sliding)	33.4	181	173 (no rolling & sliding)	4.4
Field, flat straw, 10km/h	448	375	16.3	249	278	11.6

This model would predict soil displacement within an acceptable error level of 20%. Standing stubble could reduce rolling and sliding components of soil movement. The flat straw also affects the rolling displacement of soil. When standing stubble and flat straw exist, the relationship between rolling and sliding displacement and the speed of tillage operation still remains to be studied. In other words, the effect of stubble and flat straw on the rolling and sliding displacement is not clear yet. For the tillage speed of 5 km/h, experimental results suggest that excluding rolling and sliding displacement from the total displacement of soil is appropriate when flat straw exists. When the speed of tillage operation increases to 10 km/h, adding rolling and sliding displacement into the total soil displacement would provide better accuracy in predicted results of soil displacement if surface straw exists.

The rolling and sliding displacement in this model is based on the assumption that the frictional coefficient between the system of soil blocks and the soil surface was constant no matter if straw appears on the soil surface. Therefore, it is necessary to study the effect of surface straw on the frictional coefficient between soil blocks and soil surface. Besides, the impact of soil block's landing on the rolling and sliding, and block breaking is also to be studied.

5 CONCLUSIONS

The model of soil movement by tillage was studied with a single sweep tool. The conclusions can be drawn as follows:

1. A three-dimensional model of soil movement for a single sweep was developed. The conditional parameters included in this model were geometric parameters of the tool, and the soil failure angle, which depends on the internal friction angle of the soil. The operational parameters included in this model were tool operating speed and depth.
2. The model describes soil movement as three phases of displacement. Each phase of displacement was mathematically described based on physical interactions. The soil displacement calculated with this model predicts both the forward and lateral displacement of soil by a single sweep tool.

3. The effect of surface straw on soil displacement was incorporated into the model through the impact of straw on soil rolling and sliding movement. The surface straw includes flat straw and standing stubble. Further study is required.
4. Both the soil bin and field experimental results were used to validate the model, and the results of validation showed that this model effectively predicted the forward and lateral displacement of soil by a single sweep with a relative error of 19% and less depending on the operational conditions. The main advantage of this model is that it is simple, and all calculations could be completed using a spreadsheet program.

6 REFERENCES

Beer, F. P. and E. R. Johnston. 1977. *Vector Mechanics for Engineers: Dynamics* SI Edition. McGraw-Hill INC.

De Alba, S. 2001. Modeling the effects of complex topography and patterns of tillage on soil translocation by tillage with mouldboard plough. *Journal of Soil and Water Conservation*. 56(4): 335-345.

Gill, W. R. and G. E. V. Berg. 1968. *Soil dynamics in tillage and traction*. Agriculture Research Service. Washington D. C., Department of Agriculture, US.

Govers, G., K. Vandaele, P. J. J. Desmet, J. Poesen, and K. Bunte. 1994. The role of tillage in soil redistribution on hillslopes. *European Journal of Soil Science* 45:469-478.

Lindstorm, M. J., W. W. Nelson, and T. E. Schumacher. 1992. Quantifying tillage erosion rates due to moldboard plowing. *Soil & Tillage Research*. 51: 261-277.

Liu, J., R. L. Kushwaha, D. A. Lobb and Y. Chen. 2004. Steady-state models for the movement of soil and straw during tillage. CIGR International Conference, Oct. 11-14, 2004, Beijing, China.

Lobb, D. A., R. G. Kachanoski, and M. H. Miller. 1995. Tillage translocation and tillage erosion on shoulder slope landscape positions measured using Cs-137 as a trace. *Canadian Journal of Soil Science*. 75: 211-218.

Lobb, D. A. and R. G. Kachanoski. 1999. Modeling tillage translocation using step, linear-plateau, and exponential functions. *Soil & Tillage Research*. 51: 261-277.

Rahman, S. 2004. Soil movement and manure placement from liquid manure injection tool. Unpublished Ph.D. thesis. Winnipeg, MB: Department of Biosystems Engineering, University of Manitoba.

Sharifat, K. 1999. *Soil translocation with tillage tools*. Ph.D. thesis. University of Saskatchewan.

Soehne, W. 1956. Some principles of soil mechanics as applied to agricultural engineering. Grundlagen der Landtechnik 7:11-27.

Torri, D. and L. Borselli. 2002. Clod movement and tillage tool characteristics for modeling tillage erosion. *Journal of Soil and Water Conservation*. 57(1): 24-28.

CHAPTER 5

Modeling of Soil and Straw Redistribution by a Single Sweep Tool

ABSTRACT

Soil and straw redistribution after tillage with a single sweep was modeled through developing a straw displacement model and incorporating a soil displacement model developed prior to this study. The model was validated by a soil bin experiment using a single 325-mm-wide sweep. Straw displacement by tillage with a sweep was assumed as three phases, namely forced, projectile, and overturning displacement. Mathematical relationships were established for each phase based on the physical process of the soil and straw interaction. The parameters included in the model of straw displacement were soil properties, straw length, tool geometry, and the depth and speed of tillage operation. The model was validated with the results from the soil bin experiment at the speed of 5 km/h. Results showed that the model of straw displacement had an accuracy level of 75% to 95% when predicting the forward displacement for different lengths of straw, and the accuracy was 78% and greater for predicting the lateral displacement. The parameters described by the soil and straw redistribution model included the ridge height, furrow width, furrow depth, and the width of soil disturbance. This model was validated using the experimental results from a soil bin under speeds 5, 7.5, and 10 km/h. The maximum relative error was 16% when calculating the width of soil distribution, and 40% for the ridge height. Lower speed showed less error. Straw burial was also calculated using the soil and straw displacement models, and relative error was 11%.

1 INTRODUCTION

Tillage operation impacts soil distribution and crop residue cover, which are important in many topics such as incorporating manure and protecting soil from erosion. The study of soil and straw interaction during tillage has progressed slowly due to its complexity: it involves many factors, such as soil properties, types of tillage tools and their operational parameters, and residue conditions as well. The basic knowledge of this interaction ought to include a mathematical explanation of soil and straw redistribution by tillage and how the residue cover is related to the tillage implement and its parameters.

The relationship between a tillage system and the amount of crop residue to be placed on a soil surface or buried into soil has become an important issue associated with crop residue management for efficient crop production and optimum erosion control. To acquire this relationship, studies have been carried out, but all previous studies were experimental. Gregory et al. (1982) attempted to quantify the effect of tillage on the crop residue cover by deriving a tillage equation that includes the initial fraction of surface cover, tillage tool dimensions, and soil and tillage operational parameters. Eventually, this equation was improved and simplified (Koohestani and Gregory, 1985; Wilkins et al., 1983). However, all coefficients in these equations were statistically determined based on field experimental data. Soil movement was not considered. It is impossible to apply these models to new tool design.

Soil redistribution or disturbance by tillage was also experimentally studied. McKyes (1985) described results of soil disturbance study, and indicated that the shape, width and rake angle of tools strongly influence the transport and mixing of soil particles; the throwing of soil to the sides of a tool rises also with the square of tillage speed. Dowell et al. (1988) found that the ridge height and lateral distance of soil by a sweep increased with travel speed. Hanna et al. (1993) concluded that higher speed and larger rake angle in sweep resulted in more movement of soil to build higher ridges. Sharifat and Kushwaha (1999) measured soil profile after tillage with a single tool in a soil bin under different soil moisture contents and bulk densities, and proposed a soil lateral displacement index. Modeling of soil and straw redistribution is not currently available. Developing physically based mathematical models to quantitatively describe the soil and straw redistribution is very important for both designing new tools and managing tillage practices to optimize crop residue and reduce erosion.

This study was conducted using a cereal straw and a sweep type of tool. The objectives of this study were:

a) To develop a mathematical model of straw displacement for a single sweep;

b) To develop a mathematical model of soil and straw redistribution after the tillage with a single sweep; and,

c) To validate these models by a soil bin experiment.

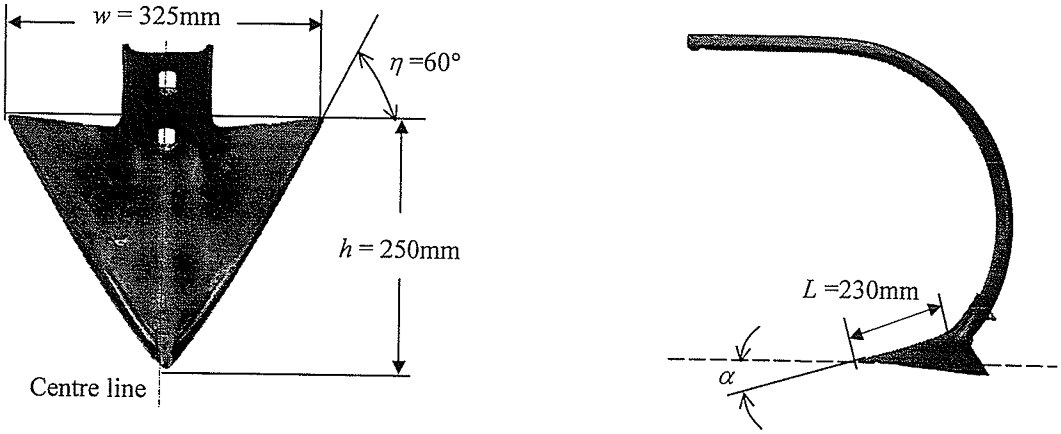
2 MODEL DEVELOPMENT

2.1 Experimental Examination of Straw Movement

2.1.1 Experimental Conditions

The observation of straw movement was conducted in an indoor soil bin, which is located at the Department of Biosystems Engineering, University of Manitoba, Canada. The dimensions of the bin are 15 m long and 1.75 m wide. Two rails on each side of the bin support a tool carriage, which is powered by an electric motor. The bin is 0.5 m deep, and is filled with loamy sand soil to a depth of 0.4 m. A full width rotary tiller drawn by the carriage is used for tilling through the width and length of the bin to loosen soil after each tillage operation. An iron plate and a plain roller, which can be mounted on the carriage, are used for leveling and packing the soil. The average moisture content of the soil was 16.3% with standard deviation of 1.2%, and the average bulk density was 1220 kg/m^3 (dry mass) with standard deviation of 53 kg/m^3 over entire experiment. The tillage tool was a 325-mm wide sweep (Fig. 1).

Oat straw was cut into different lengths and stored separately. A plot was a 325-mm long rectangular area. The length of a plot was in the direction of tool travel, and the width was three times of the tool width. One length of straw was applied and laid flat on the soil surface to represent crop residue, and its amount was 0.108 kg/m^2. Colored straw was applied in the central third area of a plot to observe their movement. Each plot was tilled once along its central line. The sweep was operated at several speeds from 3 to 10 km/h to observe the interactions, and operating depth was kept at 100 mm.



(*a*) (*b*)

Figure 1. (*a*) The sweep (McKay 50-12K) and (*b*) the shank used in the experiment

To observe the three-dimensional movement of soil and straw, three video cameras were mounted on the tillage implement during tillage. The first one was located at the centre of the front tool beam; the second one was located at the side of the tool; and the third was on the top of the tool. The analysis of these motion pictures provided optical observations of tool–soil–straw interaction.

2.1.2 Process of Tool, Soil, and Straw Interactions

Straw interacted with the tool through the soil blocks being moved by the tool. Straw movement was controlled by the movement of soil. Straw stayed on the soil surface, and moved together with soil blocks. The projectile motion of soil blocks increased with increasing tillage speed, and the increased soil projection pushed straw further. For the tool and the soil conditions used in this study, the projection of soil blocks appeared to occur when the tillage speed was higher than 3 km/h. For the tillage speed lower than 3 km/h, soil projection could be ignored. One important action was straw overturning. That is, straw pieces could be overturned by soil movement. Both straw and soil could not be overturned when tillage speed was very low, and then most straw pieces would be left on the soil surface after tillage.

If tillage speed was 5 km/h, soil projection occurred. Observed straw displacement or straw disturbance was always larger than that of the soil. Figure 2 shows the soil and straw distribution before and after tillage. Dotted lines show the outlines of soil and straw disturbance. The straw originally located in the central third area was redistributed to a wider area compared to the distribution of soil meaning that the lateral displacement of straw is larger than that of soil.

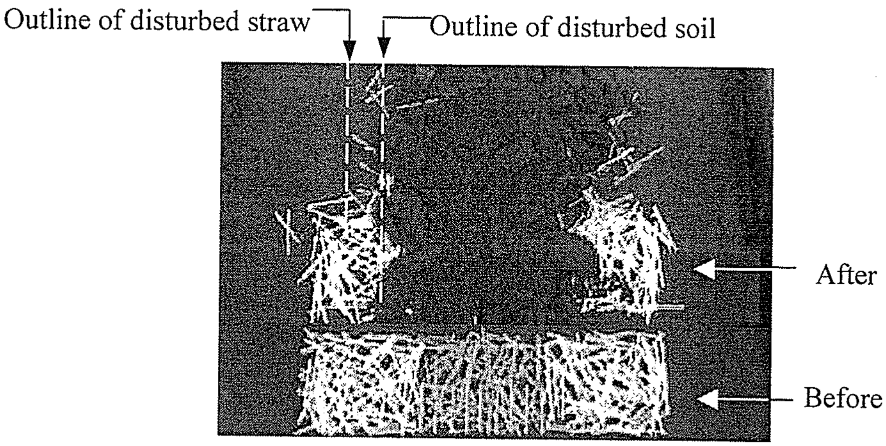


Figure 2. Soil and straw (100 mm long) distribution before and after one pass using a 325-mm-wide sweep at 5 km/h and 100 mm deep in soil bin experiment

2.2 Conceptual Model of Straw Movement

According to the observation of soil and straw interaction, straw movement was simplified as three phases: forced, projectile, and overturning movement. Once soil was lifted onto the tool, soil blocks were forced moving over the tool surface, and straw pieces were also forced to move with soil blocks. Soil blocks were projected after they left the tool; and at the same time, straw pieces were also projected. Straw overturning occurred when soil blocks were projected. The rotation of soil blocks, which was caused when it moved onto a tool, caused straw overturning. Actually, straw in front of soil failure zone was also forced to move on the ground, but the effect this movement on straw incorporation was neglected in this study.

Each phase of movement causes displacement, which consists of forward and lateral components. As a result, the vector of straw displacement can be represented by:

$$\mathbf{R} = \mathbf{R}_F + \mathbf{R}_p + \mathbf{R}_O \tag{1}$$

where $\mathbf{R}_F$ = Forced displacement,

$\mathbf{R}_P$ = Projectile displacement, and

$\mathbf{R}_O$ = Overturning displacement.

2.3 Modeling Straw Displacement

To analyze straw movement, the sweep is simplified as pyramid with a triangular base. Soil and straw with the tool were then set in a 3 dimensional Cartesian coordinates (Fig. 3), and x and y represent forward and lateral displacement respectively. Vertical displacement was not taken into account in this study. Generally, equation 1 can be rewritten as follows to represent forward and lateral displacement:

$$R_X = R_{FX} + R_{PX} + R_{OX} \tag{2}$$

$$R_Y = R_{FY} + R_{PY} + R_{OY} \tag{3}$$

2.3.1 Forced Displacement

The soil block model proposed for soil movement (Chapter 4) is employed for analyzing the forced displacement of straw. The movement of any point on the tool is possible to be derived, but the central line C_1C_2 on the tool surface *ABT* (Fig. 3) is used to represent the average movement of soil and straw. Figure 4 shows the geometric relations of tool, soil and straw in a normal plane *ABT* passing line C_1C_2. Soil blocks have angular and transitional motions while moving along the tool surface. Straw located on the soil surface is forced to move accordingly. Therefore, the forced displacement consists of two components. One is the displacement caused by forcing soil and straw up onto the tool, and the mass centre of straw is shifted horizontally. The other component is caused by the rotation of soil blocks, which also displaces straw. As a result, the forced displacement can be derived as:

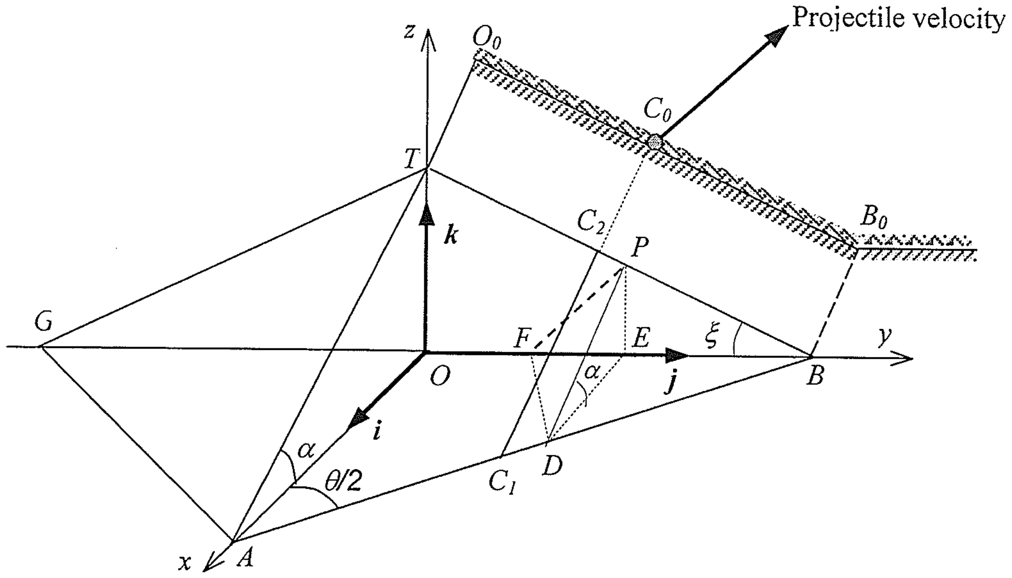


Figure 3. Coordinate and the definitions of geometric parameters for a sweep tool

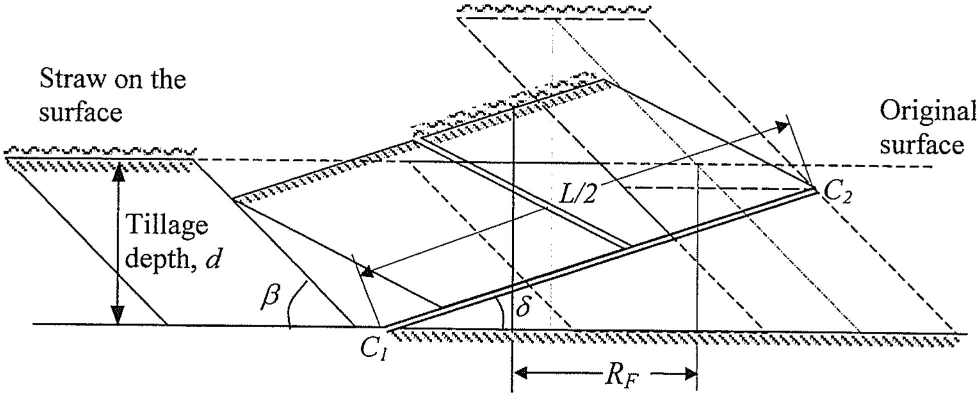


Figure 4. A block model and forced displacement of straw

$$\begin{cases} R_{FX} = d\dfrac{\cos(\beta-\alpha)-\cos\beta}{\sin\beta} + \dfrac{L}{2}(1-\cos\alpha) \\ R_{FY} = d\dfrac{\cos(\beta-\xi)-\cos\beta}{\sin\beta} + \dfrac{w}{4}(1-\cos\xi) \end{cases} \tag{4}$$

Where, w = tool width (Fig. 1a),

ξ = inclined angle of tillage tool to x-axis,

β = soil failure angle, $\beta = 45° - \phi/2$,

α = incline angle of tillage tool to y-axis,

d = tillage depth, and

L = maximum length on the tool surface (Fig. 1b).

The parameters used in Equation 4 are also shown in Figures 1, 3 and 4. The forced displacement of straw is related to the dimensions and geometry of the tool, tillage depth, and the failure angle of soil.

2.3.2 Projectile Displacement

The projectile displacement of straw can be formulated according to the equations of soil projectile displacement (Chapter 4). The only difference is the initial point, which is $C_0(x_c^0, y_c^0, z_c^0)$ for straw projection. Using the same method as that of deriving soil projectile displacement, the central point on the soil surface at one side of the tool C_0 (Fig. 3) is selected to represent the average displacement of straw projection. Therefore, The equations of average projectile displacement of straw can be written as:

$$\begin{cases} R_{PX} = (x_c - x_c^0) \\ R_{PY} = (y_c - y_c^0) \end{cases} \tag{5}$$

The coordinates in Eq. 5 after projection are calculated by:

$$\begin{cases} x_c = x_c^0 + \dfrac{v_x}{g}\left(\sqrt{v_z^2 + 2z_c^0 g} + v_z\right) \\ y_c = y_c^0 + \dfrac{v_y}{g}\left(\sqrt{v_z^2 + 2z_c^0 g} + v_z\right) \\ v_x = V_B \cos(\beta - \alpha) \\ v_y = V_B^y \cos(\beta - \xi) \\ v_z = V_B^y \sin(\beta - \xi) \\ V_B = \dfrac{\sin\alpha}{\sin\beta} v_t + \dfrac{\sqrt{2}}{2} \alpha v_t \\ V_B^y = V_B \sin(\beta - \alpha) + \dfrac{\sqrt{2}}{2} \xi v_t \end{cases} \tag{6}$$

2.3.3 Overturning Displacement

The rotation of soil blocks causes straw overturning, which results in the further displacement of straw. One-pass tillage with a single tool can not overturn straw twice as air resistance and gravitational forces exist. Hence, the average displacement of straw overturning is a half of the straw length no matter how far the soil blocks roll. The direction of straw overturning is assumed as perpendicular to the edge of the tool as shown in Fig. 5. As a result, the overturning displacement can be resolved into forward and lateral components as follows:

$$\begin{cases} R_{OX} = 0.5l\sin\dfrac{\theta}{2} \\ R_{OY} = 0.5l\cos\dfrac{\theta}{2} \end{cases} \tag{7}$$

where, l is straw length, and θ is the nose angle of the sweep.

Equation 7 indicates that the overturning displacement is directly related to the nose angle of the sweep. Larger nose angle would produce larger forward displacement for the same length of straw. Equations 6 and 7 include soil properties, geometric parameters of tool, and straw size.

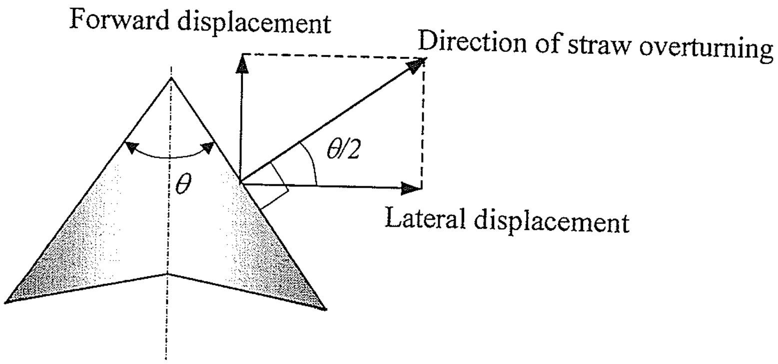


Figure 5. The relation of assumed direction of straw overturning and tool geometry

2.4 Modeling Soil and Straw Redistribution by Tillage

2.4.1 Simplified Soil Profile

Soil was redistributed by a sweep and then formed two ridges after a single tool passed as shown in Fig. 6. The space between these two ridges is called a furrow, so these two ridges are symmetrical to the furrow centre. The ridge shown in Fig. 6 has two bottom angles, φ_{in} and φ_{out}. φ_{in} indicates the angle inside the furrow; and φ_{out} is the other side. Point *C* is the central point of right wing of the tool's two wings. The point *C* is also the point, which was selected as a representative point to calculate the average soil displacement. When the tool passes, the soil blocks are removed from the point *C* and relocated at the point *D*. The distance *e* in Fig. 6 is the average lateral soil displacement. The parameters describing the soil profile include the furrow width ($2b_0$), the width of soil disturbance ($2b$), the ridge height (h), and the furrow depth (h+d_1).

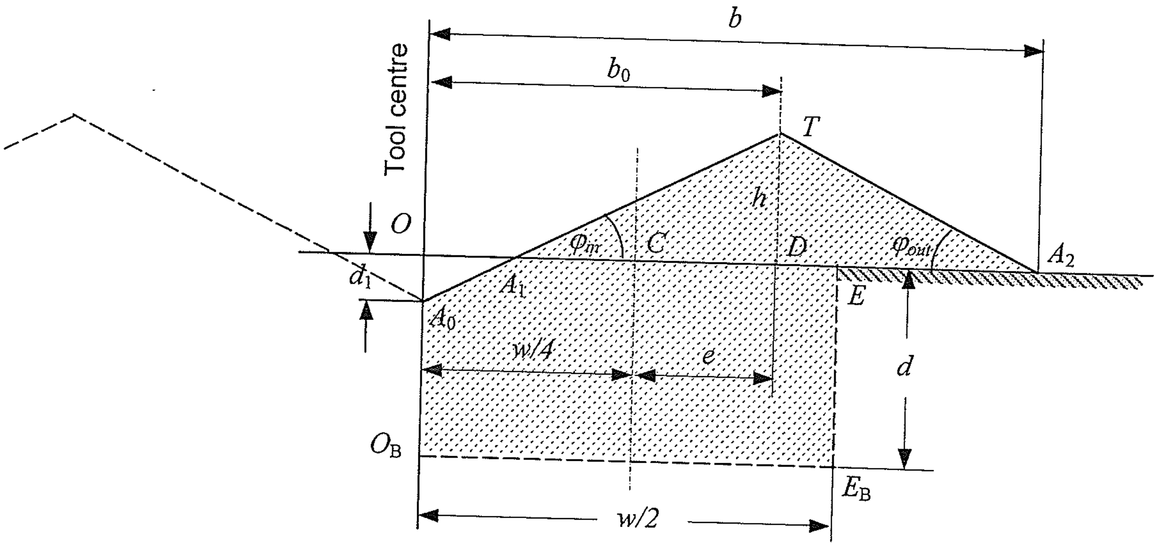


Figure 6. Geometric relations of soil redistribution after tillage operation with a sweep tool (*d*: tillage depth; *w*: tool width)

2.4.2 Hypotheses

Two assumptions are made to determine those model parameters. First, the profile of soil distribution (Fig. 6) after tillage operation with a single sweep is simplified as an isosceles triangle with bottom angle of $\varphi_{in} = \varphi_{out} = \varphi$, which is referred to as a pile angle. The A_1TA_2 in Fig. 6 is named the pile of soil.

Second assumption is the soil expansion, which is described as follows. Assuming that the soil mass in the tool region OO_BE_BE consists of a number of cubes with the edge length of a (Fig. 7). After the tool passed, these cubes are randomly redistributed, and each cube occupies a space of a ball with the diameter of $\sqrt{2}a$. All the cubes are rearranged as a stack of balls. The spaces between the balls are eliminated. Each cube occupies an extra space. Thus, the redistribution of these soil cubes results in an expansion of soil volume.

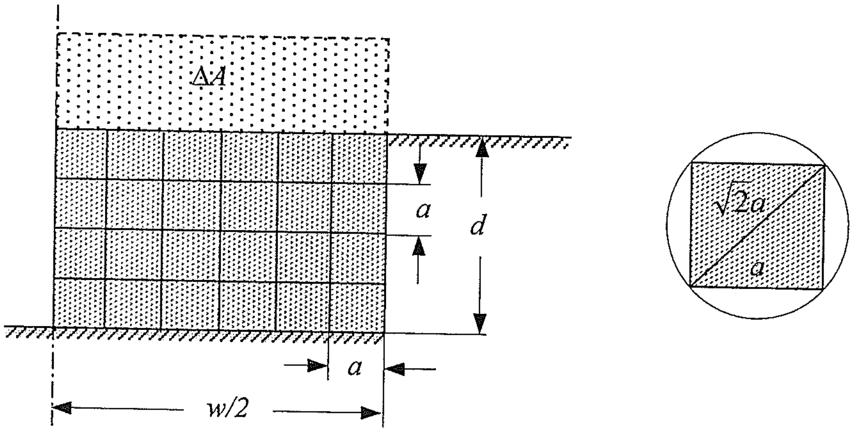


Figure 7. Assumption of soil expending after tillage operation

2.4.3 Analytical Model

According to the simplified ridges, geometric relationships of those parameters in Fig. 6 are derived as follows:

$$h+d_1=\left(\frac{w}{4}+e\right)\tan\varphi \tag{8}$$

$$b=(2h+d_1)\cot\varphi \tag{9}$$

There are three unknown parameters b, h and d_1 in equations 8 and 9. One more relationship is needed to determine the soil profile. The third relationship is derived based on the second assumption. To simplify following derivation, two-dimensional expression is used here. The extra area occupied by each square is:

$$\Delta A_0=\left(\frac{\pi}{2}-1\right)a^2 \tag{10}$$

Therefore, the total area expended is:

$$\Delta A=\left(\frac{\pi}{4}-\frac{1}{2}\right)wd \tag{11}$$

The expanded area is distributed in the "pile" area A_1TA_2. That is, the expanded area plus area OA_0A_1 are equal to the area of A_1TA_2. As a result, we have the third relationship required to determine the parameters of soil profile as following.

$$\left(h^2-d_1^2\right)\cot\varphi=\left(\frac{\pi}{4}-\frac{1}{2}\right)wd \tag{12}$$

Substituting Eq. 8 into Eq. 12 to eliminate d_1, then the height of the pile can be solved. Hence, all the parameters in Fig. 6 are determined. That is,

$$h=\frac{(\pi-2)wd}{2w+8e}+\frac{1}{2}\left(\frac{w}{4}+e\right)\tan\varphi \tag{13}$$

$$b=h\cot\varphi+\left(\frac{w}{4}+e\right) \tag{14}$$

$$b_0=\left(\frac{w}{4}+e\right) \tag{15}$$

$$d_1 = \left(\frac{w}{4} + e \right) \tan \varphi - h \tag{16}$$

The parameter b is the most important one in describing the soil distribution by tillage, and $2b$ is usually called the width of soil disturbance. Soil distribution model (Eqs. 13 and 14) included operational parameters of tillage (depth and speed), soil property parameter (frictional angle φ), and geometric parameters of the tool. The effect of straw on the soil distribution is reflected by the average of lateral soil displacement (e). Equation 14 indicates that the width of soil disturbance increases with increasing tillage speed. The ridge height, however, would slightly increase when the speed increases. The final format of this model does not include the size of soil block though it was assumed in deriving Eq. 12.

2.4.4 Modeling Straw Burial

Straw is also redistributed by tillage. The final location of a straw piece depends on its displacement. Using the central point on one wing of a tool as an indicator of average displacement (e_r), then the average lateral displacement would be located at a point (D_R) between C and A_2 (Fig. 8). The length of straw and the geometric relationship between the location of D_R and the tool area OE determined the portion of the straw distributed inside and/or outside of OE. No matter where the straw is distributed, the straw originally located in the area OE is shifted laterally to $O'E'$, and the straw located in the area OA_2 after tillage would be buried. The portion of straw located at $O'E$ is to be mixed up with the soil in the tool region.

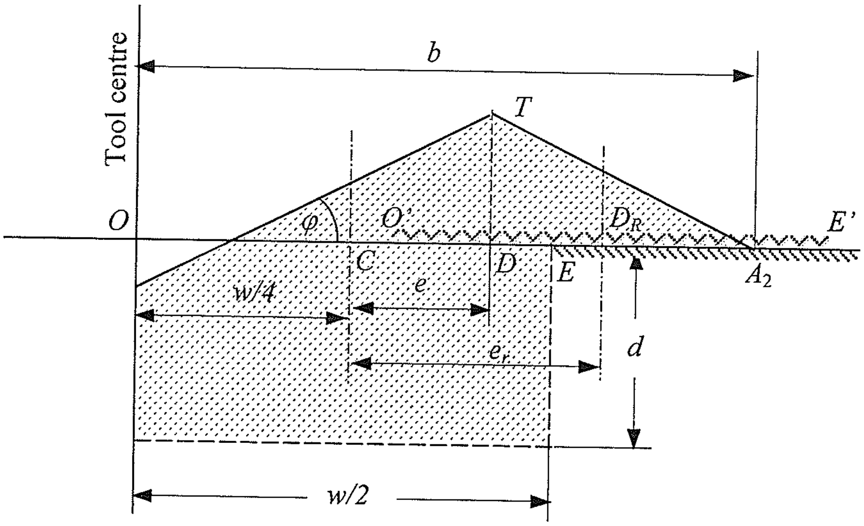


Figure 8. Geometric relations of soil and straw redistribution after tillage operation with a sweep tool (*d*: tillage depth; *w*: tool width)

The position of point D_R (Fig. 8) indicates where the straw is distributed after tillage with a single sweep. Average lateral displacement e_r is the central position (D_R) of the straw relocated. The width of straw redistributing band *O'E'* is determined by the difference of lateral projectile displacement between the top point O_0 and bottom point E_0 on the surface of the tool (Fig. 11). That is, a part of the straw located at *O'E* is to be mixed up in the tool area OEO_BE_B, and the rest part will be buried on the untilled soil surface along EA_2 (Fig. 8). According to the equation of straw lateral displacement, the width of straw distributing band was written as:

$$W_{O'E'} = \frac{w}{2} + l + \frac{v_y}{g}\left(\sqrt{v_z^2 + 2z_{O_0}^0 g} - \sqrt{v_z^2 + 2z_{E_0}^0 g}\right) \qquad (17)$$

Equation 16 indicates that the width of straw distribution $W_{O'E'}$ is wider than one half of the tool width. It is necessary to mention that the $W_{O'E'}$ in Eq. 17 is measured from the centre of straw length. Hence, the width of straw distribution should be the length between O' and E' plus one length of the straw if the width is measured from the outline of straw distribution, such as the outline of the straw movement presented in Fig. 2.

3 MODEL VALIDATION

3.1 Materials and Methods

A soil bin experiment was conducted to validate the models developed in this study. The soil bin and its soil conditions were the same as described in Section 2.1, and the tool was also the same sweep (Fig. 1). Oat straw was selected as a crop residue.

3.1.1 Straw

Oat straw was cut into different lengths from 50 mm to 250 mm with increments of 25 mm. To minimize the number of plots and test runs, three straw mixtures were adopted for the experiment, i.e. mixture 1 contains three lengths: 50, 125, and 200-mm-long straw; mixture 2 consists of 75, 150, and 225-mm-long straw; and 100, 175, and 250-mm-long straw mixed into mixture 3. No matter which mixture, there were 300 pieces straw in total, and 100 pieces for each length. The amount of straw distribution was kept at 0.108 kg/m^2 for every mixture by adjusting the area of straw distribution. In addition, to examine the impact of different lengths in a mixture one on another, single-sized straw was also applied to measure straw displacement. The single-sized straw means that all straw pieces in a plot had the same length.

3.1.2 Experimental Design

To validate the model of soil redistribution by the single sweep, the experiment was conducted at three speeds: 5, 7.5, and 10 km/h. Tool operating depth was 100 mm and kept constant for each run. The soil bulk density and moisture content were also maintained constant. Three straw mixtures combine three speeds formed nine treatments, and each treatment was replicated three times. Three treatments were randomly arranged in the bin.

Plot size was 0.975 m wide (three times of the tool width) and 1.5 m long. Straw was applied in a plot and laid flat on the soil surface. For all test runs, plots were tilled only once along the centre line of its width.

3.1.3 Measurements

Measurements included soil profile and straw displacement. Figure 9 shows the dimensions measured for determining a soil profile. Six sections along the direction of tool travel were randomly selected as replications.

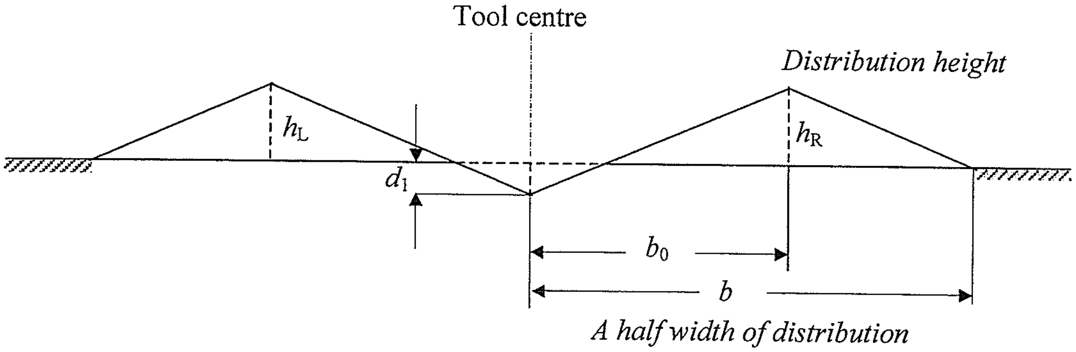


Figure 9. Geometric parameters used to determine soil profile after tillage

To measure straw displacement, nine straw tracers were laid flat on the soil surface with longitudinal and lateral orientations. The longitudinal tracer means the length of a tracer was parallel to the direction of tool travel, and lateral tracer was perpendicular. Longitudinal tracers were employed to trace the straw displacement, and the lateral tracers were used to examine the effect of tracer orientation on straw movement. All tracers were arranged in the central third area of a plot as shown in Fig. 10. After soil being prepared, tracers were set up, and their initial positions were measured and recorded. Then, straw was spread over top of the tracers. Straw tracers had different lengths, and they were the same length as those straw pieces applied in the plot.

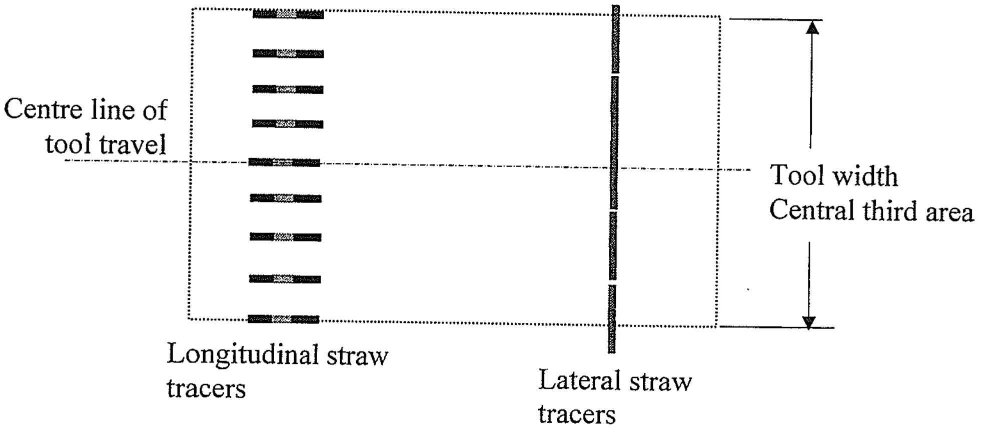


Figure 10. Tracer arrangement for measuring straw and soil displacement

3.2 Experimental Results

The straw displacement measured with straw mixtures was not significantly different with those measured by single-sized straw analyzed by one way ANOVA with Duncan test at significant level of 0.1. The straw displacement measured with lateral tracers had large variances and was numerically larger than those measured with longitudinal tracers. Statistical analysis did not detect any significant difference between straw displacement measured with longitudinal and lateral straw tracers for any length of straw. For this reason, the data of straw displacement presented below was measured with longitudinal tracers.

Both forward and lateral straw displacement was increasing with increasing straw length (Table 1). However, the trend of increase was not significant. Standard deviations of three replications were also provided in Table 1. For some straw lengths, variances in results were large. The possible reason was the effect of the shank on soil and straw movement. The shank could cause extra displacement by two actions. First, the shank could hit a tracer; and second, straw tracer could be jammed on the shank and then was dragged for a long distance. Besides, the mechanical vibration of the tool was another possible reason that contributed to the large variance.

3.3 Validating of Straw Displacement Model

To calculate straw displacement, the sweep was simplifed into a symmetric pyrism and set in a 3 dimensional Cartesian coordinate system as shown in Fig. 11. Coordinate x is the direction of tool travel, and y represents the lateral movement. The original point and its horizontal plane is the plane of the sweep bottom, which is one tillage depth below the soil surface. Tool dimentions were measured off the tool. For the tillage depth of 100 mm, the coordinates of points (O_0, C_0, *and* E_0) on the soil surface at the rear edge of the sweep can be numarized as shown in Fig. 1. The centre point C_0 is pointed to represent the average straw displacement. The soil parameters used in this model were soil failure angle β and internal friction angle (30°), and the relationship is $\beta = 45° - \phi/2$. Straw displacement is then calculated for different lengths of straw (Table 1).

The results from the experiment and the prediction indicated that the straw displacement model would predict the straw displacement. Compared to those measured values, calculated displacement of longer straw had greater error; for all the lengths of straw used in the experiment, the error is in the range of 1.2% to 25.2% under the conditions used in this study. For 150 mm and longer straw, the model underestimated the forward straw displacement. The error of predicting lateral displacement is 22.4% and less. Those greater errors could be caused by experimental error.

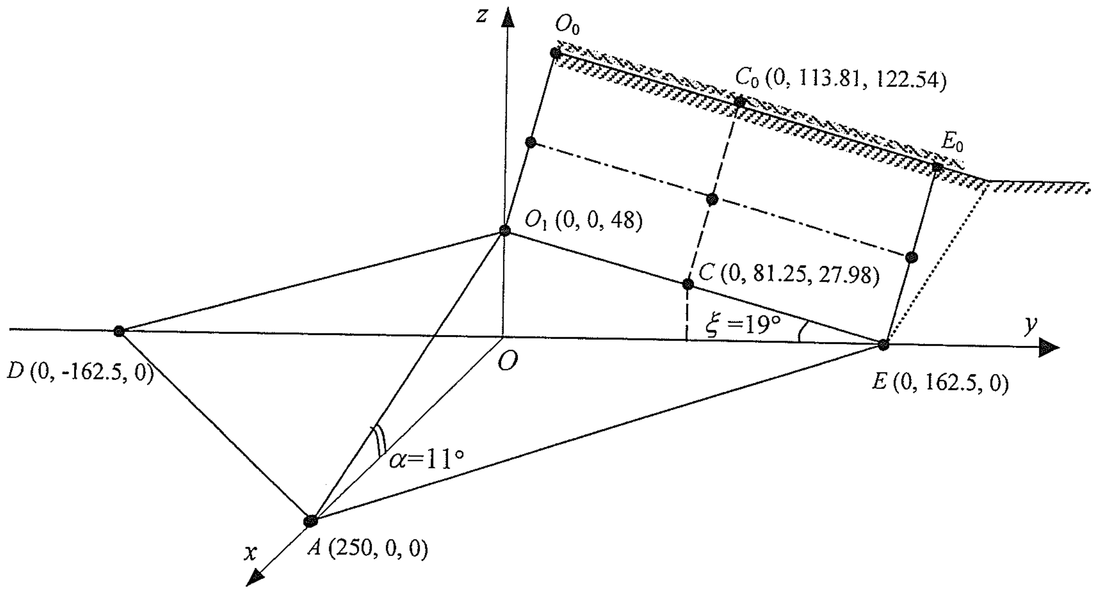


Figure 11. Coordinate system of the sweep for calculating straw displacement

3.4 Validating of Soil Redistribution Model

Based on the calculation of soil lateral displacement, the soil redistribution after the tillage with the single 325-mm-wide sweep was calculated. The pile angle was determined as $\varphi = 25°$ by measuring the pile angle of the experimental soil. Soil was piled up using the same tillage tool operated at the speed of 5 km/h for a several passes. Primary parameters of soil profile were given in Table 2 to compare with those measured values. Experimental results showed that the width of soil distribution significantly increases when tillage speed increases. The measured height of soil distribution slightly decreases as speed increases, but it is not significant. The calculated height tends to increase as speed increasing. The comparison showed that the model of soil redistribution by a single sweep could predict the width of distribution ($2b$), and its relative error is 16% and less for the three speeds 5, 7.5 and 10 km/h; but, calculated h and b_0 has approximately maximum error of 40% at the speed of 10 km/h. For the speeds of 5 and 7.5 km/h, the errors of calculating all three parameters are less than 21%. It could be concluded that the soil redistribution model works well when the tillage speed is lower than 7.5 km/h; but it is not appropriate if speed reached to 10 km/h.

The inadequacy is mainly caused by the assumption of isosceles triangle of a ridge. Sharifat and Kushwaha (1999) measured soil profile in a soil bin using the same sweep (McKay 50-12K) with the one used in this study. The results indicated that the soil profile could be simplified as an isosceles triangle if the tillage speed is 5 km/h. However, experimental results indicated that the outer bottom angle φ_{out} was tending to be smaller than the inner angle with increasing tillage speed.

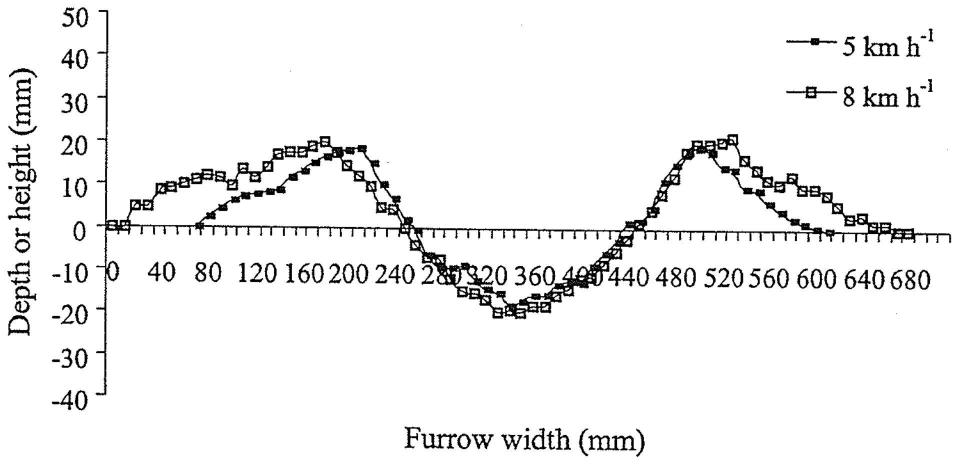


Fig. 12 Soil profile at 5 and 8 km/h speed and 10.3% soil moisture and 205 kPa Cone Index (Sharifat and Kushwaha, 1999).

Figure 12 showed the results measured at two speeds. It is believed that the pile angle varies with tillage speed, which affects lateral soil rolling and sliding during landing. The model developed in this study did not reflect the possible change of this angle. As a result, the calculated pile height was higher than the one measured. Besides, the height of soil pile measured tends to decrease with increasing tillage speed; but this model did not predict this change.

Table 1 Comparison of calculated and measured average straw displacement by the 325-mm-wide sweep on loamy sand soil (tillage depth: 100 mm, speed: 5 km/h)

Straw length (m)	**Forward displacement** (m)			**Lateral displacement** (m)		
	Measured (Std. Deviation)	Predicted	Relative error (%)	Measured (Std. Deviation)	Predicted	Relative error (%)
0.050	0.143 (0.023) *b**	0.172	20.2	0.162 (0.022) *c*	0.129	20.7
0.075	0.204 (0.071) *ab*	0.179	12.0	0.180 (0.040) *bc*	0.139	22.4
0.100	0.173 (0.053) *b*	0.186	7.4	0.190 (0.018) *abc*	0.150	21.1
0.125	0.169 (0.082) *b*	0.193	14.1	0.172 (0.043) *bc*	0.160	6.5
0.150	0.246 (0.049) *ab*	0.200	18.9	0.178 (0.043) *bc*	0.171	4.1
0.175	0.218 (0.017) *b*	0.206	5.2	0.184 (0.039) *abc*	0.181	1.5
0.200	0.238 (0.026) *ab*	0.214	10.2	0.205 (0.032) *ab*	0.192	6.6
0.225	0.294 (0.078) *a*	0.220	25.2	0.200 (0.033) *abc*	0.202	1.2
0.250	0.246 (0.020) *ab*	0.227	7.6	0.224 (0.031) *a*	0.213	5.0

* The same letters followed the measured values in the same column shows no significant difference was detected by ANOVA with Duncan test at significant level of 0.1.

Table 2 Comparison of calculated and measured parameters of soil distribution by a single 325-mm-wide sweep in the soil bin (loamy sand, tillage depth: 100 mm)

	Tillage speed (km/h)	*5*	*7.5*	*10*
	Measured (Standard deviation*)	357.9 *a* # (31.4)	411.9 *b* (14.2)	488.3 *c* (18.0)
b (mm)	Predicted	343.8	440.8	566.6
	Relative error (%)	3.9	7.0	16.4
	Measured (Standard deviation)	74.6 *a* (10.2)	69.3 *a* (11.6)	68.6 *a* (41.5)
h (mm)	Predicted	69.3	80.0	96.7
	Relative error (%)	7.1	15.4	40.7
	Measured (Standard deviation)	172.0 *a* (2.1)	221.9 *b* (13.2)	257.8 *b* (10.8)
b_0 (mm)	Predicted	195.3	269.3	359.3
	Relative error (%)	13.5	21.4	39.4

* All measured results were calculated from six replicates.

\# The same letters followed the measured results in the same row show no significant difference were detected by ANOVA with Duncan test at significant level of 0.1

3.5 Straw Distribution

The width of straw distributing band *O'E'* was calculated as 149.5 mm for 100-mm-long straw with Eq. 17. The measured distribution of those 100-mm-long straw tracers was presented in Fig. 13, which matches with the photo shown in Fig. 2. The width of straw distributing band was 120 mm with standard deviation of 57 for the left side of the distribution, and 149.3 mm (standard deviation: 47) for the right side. Therefore, the model proposed in this study would also predict the distribution of straw. The average width of straw distribution for two sides was 134.7 cm, and the relative error of model calculation was then 11%.

3.6 Discussion

Soil and straw redistribution after tillage operation is important in studies of straw burial and manure incorporation. The soil and straw redistribution model was developed using a single sweep tool, but it has potential capacity to be developed for multiple sweeps. As this model is a physically based mathematical model, it would be beneficial to the studies of straw and manure handling, soil erosion, and the design of new tools.

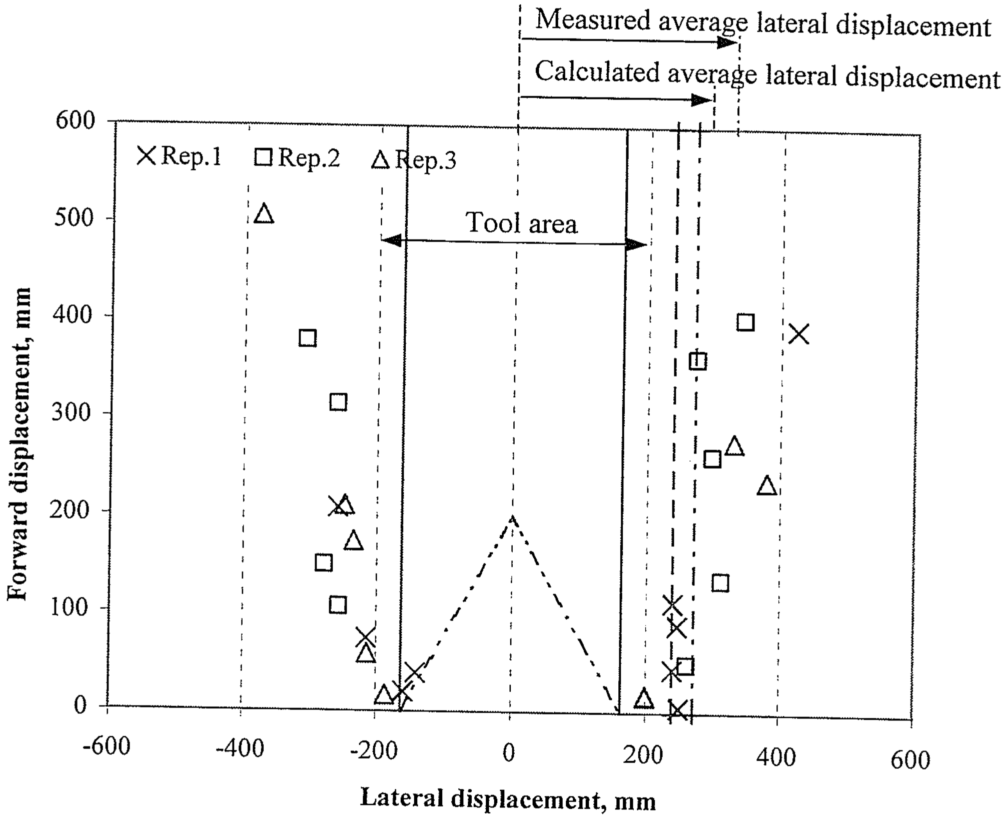


Figure 13. The distribution of 100-mm-long straw tracers after tillage with a single 325-mm-wide sweep (tillage speed: 5 km/h, depth: 100 mm)

The pile angle was used as a parameter in modeling soil redistribution by tillage. This angle could vary with the impact velocity of soil blocks at landing. Higher tillage speed creates higher landing velocity that could reduce the pile angle. This angle could also be affected by the amount of the soil forming the pile. However, this influence is still unknown, and then it was not considered in this study. Besides, the assumption of soil expansion is also to be validated for different type of soils, soil moisture contents and bulk densities.

The description of soil and straw redistribution by a single sweep is the base of studying multiple tools. If the purpose of tillage operation was only to bury all the straw, it could be completed by adjusting the tool spacing to $2b$. To partially bury straw, the tool spacing could be arranged between w and $2b$ depending on the amount of straw to be kept on the soil surface. The straw incorporation under multiple tools is being studied.

The effect of straw conditions on straw displacement and straw incorporation was not directly included in above modeling. Soil displacement is the only factor in the models, which is related to straw conditions. Further study is required.

The proposed models were developed based on a single sweep. However, the concept and method of the modeling could be used for other tools, and it is possible to be extended to other tool types with minor modifications. The major modification would be the soil projection according to the special tool geometry. All the models included the speed and depth of tool operation, but the validation was completed at a constant depth only.

4 CONCLUSIONS

Straw displacement and soil and straw redistribution by tillage with a single sweep were studied and mathematically modeled. Conclusions were drawn as follows:

a. Straw movement during tillage was simplified as three phases: forced, projectile, and overturning. The soil block model proposed for soil movement in prior study was employed in modeling straw displacement. A mathematical model of straw displacement was developed for a single sweep, which would predict average forward and lateral straw displacement for 50-mm to 250-mm-long straw. One advantage of this model is that it's simple and easy to calculate. All the calculation can be completed in a MS Excel worksheet.

b. Models were validated by a soil bin experiment at the speed of 5 km/h; and the accuracy of straw displacement model was 75% to 95% in predicting forward displacement, and above 78% when predicting lateral displacement. Experimental results of straw displacement had large variation, and the reasons were the effect of shank and mechanical vibration of carriage on straw movement. Further validation under a field conditions is required.

c. A model of soil redistribution by tillage was developed based on the assumption of soil expansion, and then the model was validated with soil bin experiments at the speeds of 5, 7.5, and 10 km/h. The comparison of measured and calculated values indicated that the model could predict the parameters of soil profile very well for the tillage speed from 5 km/h to 8 km/h, and the relative error was 21% and less.

However, the model was not suitable for the tillage speed of 10 km/h or higher due to the relative error reached to 40%.

d. Straw redistribution by a single sweep was also modeled, and it would be able to predict the average lateral displacement and the width of straw distribution. Combined with the width of soil distribution, straw burial was calculable with relative error of 11%. These parameters were more important for studying the straw incorporation by multiple tools.

5 REFERENCES

Dowell, F. E., J. C. Siemens and L. E. Bode. 1988. Cultivator speed spacing effects on herbicide incorporation. *Transactions of ASAE* 31(5): 1315-1321.

Gregory, J. M., T. M. McCarty, F. Ghidey, D. L. Pfost. 1982. Tillage equation for residue management. ASAE paper No.82-1513.

Hanna, H. M., D. C. Erbach, S. J. Marley, and S. W, Melnin. 1993. Changes in soil microtopography by tillage with a sweep. *Transactions of ASAE* 36(2): 301-307.

Koohestani, M. and J. M. Gregory. 1985. Measurement of tillage parameters that affect residue cover. ASAE paper No. 85-2045.

Sharifat K. and R. L. Kushwaha. 1999. Lateral soil movement by tillage tools. ASAE Paper No.991003. St. Joseph, Mich.: ASAE.

McKyes, E. 1985. *Soil cutting and tillage*. Elsevier Science Publishing Company Inc. 52 Vanderbilt Avenue, New York, NY10017, U.S.A.

Wilkins, D. E., C. L. Jr. Douglas, P. E. Rasmussen, and D. A. Haasch. 1983. Tillage influence on residue incorporation and soil moisture. ASAE paper No.83-1026.

CHAPTER 6

General Conclusions

The interaction of tillage tool–soil–straw was theoretically and experimentally studied with a 325-mm-wide sweep. Experimental study included two soil bin experiments and one field experiment. Three models were developed for mathematically describing the interaction between soil and straw during tillage with a single sweep. The first model (chapter 3) was developed to predict the amount of soil and straw moving with the tool; the second model (chapter 4) was developed to quantify the average distance of the soil relocated by a tool; and the third one could be used to calculate soil and straw distribution after tillage. These models were validated with a soil bin and field experiments. These models and the data obtained from experiments provided a basic knowledge required for further study. Conclusions were drawn as follows.

1. Experimental Studies

Experimental study on the interaction of tillage tool–soil–straw was conducted in a soil bin and a field with a single 325-mm-wide sweep. Conclusions were:

1.1. Straw tracers were able to represent the movement of straw, and their orientations did not significantly affect the results. Straw mixtures worked well in studying soil and straw interaction. Straw burial measured with single-sized straw did not significantly differ with that measured with straw mixtures for most lengths of straw except those shorter than 100 mm.

1.2. Three parallel passes with a single tool was used to simulate three tools, but it produced less soil and straw displacement than using three tools for both soil bin and field experiments; but, there was no significant difference detected between the three parallel passes and three tools with Duncan test at significant level of 0.1.

1.3. No significant differences were detected for straw displacements measured in the field and the soil bin even when the field had standing stubble. Longer straw had larger displacement. Straw displacement had large variances, which could be a reflection of the differences between the measurements in the field and soil bin.

1.4. The forward displacement of the field soil was 50% greater than that of the bin soil when the field had no stubble. Stubble effectively resisted soil rolling and reduced soil displacement at the speed of 5 km/h. The soil displacement in the stubble field was very close to that in the soil bin. Soil displacement was also reduced when increasing straw length, but it was not significantly different.

1.5. Soil and straw movement, and straw burial were very sensitive to the speed of tillage. The forward displacement of soil and straw reduced more than 70% and 80% respectively if tillage speed was reduced from 10 to 5 km/h.

1.6. For those straw pieces longer than 100 mm, increasing length did not significantly increase the percent of unburied straw no matter what the tillage speed was. For a specific length, the percent of unburied straw was significantly reduced when tillage speed increases.

1.7. The straw cover after tillage by three tools had a common trend of increasing with increased straw length, and this trend was linear for both the soil bin and the field (without standing stubble) experiments. The straw covers measured in the soil bin were not significantly different compared to those measured in the field except one of 250-mm-long straw. It is concluded that the soil bin could be used to simulate the field conditions in study of straw incorporation if the length of straw was shorter than 250 mm.

2. Amount of Soil and Straw Moving

2.1 Steady-state models of soil and straw movement during tillage with a single sweep were developed and validated with a soil bin experiment. These models predict the amount of soil and straw moving during tillage. McKyes and Ali's model and a two-dimensional model were also applied to the steady-state movement of soil and straw, and then a sweep model was developed.

2.2 For the tillage depth of 100 mm used in this study, the 325-mm-wide sweep was a wide tool. However, McKyes and Ali's model would predict the amount of soil moving, and its accuracy was better than others; but, the amount of straw moving was overestimated 50% and greater than the experimental results. The two-dimensional model had minimum relative error of 43% in predicting the area of straw moving. The accuracy of McKyes and Ali's model in predicting the amount of soil moving could be a coincidence due to modeling error.

2.3 The sweep model proposed in this study would predict the amount of moving soil with relative error of 22% and less. In prediction of straw moving area, the maximum relative error of the sweep model was only 12%. This sweep model, however, was specially developed and validated for sweep tools. Further study is required to develop suitable models for other type of tools.

3. Soil Movement

The model of soil displacement was developed for a single sweep tool. The conclusions were as follows:

3.1 A three-dimensional model of soil movement for a single sweep was developed. The conditional parameters included in this model were geometric parameters of the tool, and the soil failure angle, which depends on the internal friction angle of the soil. The operational parameters included in this model were tool operating speed and depth.

3.2 The model describes soil movement as three phases of displacement. Each phase of displacement was mathematically described based on physical interactions. The soil displacement calculated with this model predicts both the forward and lateral displacement of soil by a single sweep tool.

3.3 The effect of surface straw on soil displacement was incorporated into the model through the impact of straw on soil rolling and sliding movement. The surface straw included flat straw and standing stubble. Further study is required.

3.4 Both the soil bin and field experimental results were used to validate the model, and the results of validation showed that this model effectively predicted the forward and lateral displacement of soil by a single sweep with a relative error of 19% and less depending on the operational conditions. The main advantage of this model is that it is simple, and all calculations could be completed using a spreadsheet program.

4. Straw Incorporation

Straw displacement, and soil and straw distribution after tillage with a single sweep were studied and mathematically modeled. Conclusions can be drawn as follows:

4.1 Straw movement during tillage was simplified as three phases: forced, projectile, and overturning. The soil block model proposed for soil movement in prior study was employed in modeling straw displacement. A mathematical model of straw displacement was developed for a single sweep, which would predict average forward and lateral straw displacement for 50 to 250-mm-long straw. One advantage of this model is that it's simple and easy to calculate. All the calculation could be completed in a MS Excel worksheet.

4.2 Models were validated by a soil bin experiment at the speed of 5 km/h; and the accuracy of straw displacement model was 75% to 95% in predicting forward displacement, and above 78% when predicting lateral displacement. Experimental results of straw displacement had large variation, and the reasons were the effect of shank and mechanical vibration of carriage on straw movement. Further validation under a field conditions is required.

4.3 A model of soil redistribution by tillage was developed based on the assumption of soil expansion, and then the model was validated with soil bin experiments at the speeds of 5, 7.5, and 10 km/h. The comparison of measured and calculated values indicated that the model could predict the parameters of soil profile very well for the tillage speed from 5 km/h to 8 km/h, and the relative error was 21% and less.

However, the model was not suitable for the tillage speed of 10 km/h or higher due to the relative error reached to 40%.

4.4 Straw redistribution by a single sweep was also modeled, and it would be able to predict the average lateral displacement and the width of straw distribution. Combined with the width of soil distribution, straw burial was calculable with relative error of 11%. These parameters were more important for studying the straw incorporation by multiple tools.

5. The Future Work

5.1 The experiment of measuring the amount of moving soil and straw by the sweep conducted in the soil bin is to be studied to obtain more accurate experimental data. The experimental results in this study overestimated the amount of moving soil and straw. This overestimation was caused by the measurement method adopted in the experiment, that was the open hole in soil. Soil collapse always happened in the front edge of the hole when a tool passed it. The collapse caused more soil moved in the hole that was counted as moving soil. Besides, the sharp change of media resulted in the change of soil and straw moving pattern. This was also the reason of experimental error.

5.2 The model of soil movement requires further studies. This model would predict soil displacement with an acceptable error. The standing stubble could stop soil rolling. When standing stubble exists, the displacement of soil should not include the component of rolling and sliding displacement when the speed of tillage operation is low. However, the relationship between rolling and sliding displacement and the speed of tillage operation is still remaining to be studied when straw exists. In other words, the effect of straw on the rolling displacement is not clear yet.

5.3 The model of straw incorporation requires more effort. The pile angle was used as a parameter in modeling soil distribution after tillage. This angle could vary with the landing velocity of soil blocks. Higher tillage speed creates higher landing velocity. Hence, the pile angle could be affected by the tillage speed. This angle could also be affected by the amount of the soil forming this pile. Nevertheless, this influence was not clear, and was not considered in the proposed model. It is to be studied. Besides, the assumption of soil expansion in Chapter 5 is also to be validated for different types of soils and soil cloddiness.

5.4 In the case of multiple tools, the description of soil and straw distribution by the tillage operation with a single tool indicated how the tool spacing should be arranged according to the purposes of tillage operation. If the purpose of tillage operation is only to bury all the straw, tool spacing should be equal to the width of disturbance ($2b$). To partially bury straw, the tool spacing should be arranged between tool width (w) and $2b$ depending on the amount of straw to be kept unburied. The straw incorporation under multiple tools is being studied.