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RESEARCH PAPER

Development of spot plow providing complete inversion for effective weed control

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ABSTRACT

Tillage for 'complete inversion' of soil *i.e.* overturning soil slices 180° was proposed, a 'spot plow' was developed and tested to accomplish the task, and a simulation model were evaluated to demonstrate the efficacy of the plow on weed control. A 360 mm-wide spot plow was designed to operate at a speed of 1.9 m s^{-1} for the spot plowing with the least possible lateral displacement of soil slice by utilizing inertia of the soil slice and securely rotating it. In field experiments, complete spot inversion required an operating speed of at least 1.6 m s^{-1}; at lower speeds a portion of the soil block was left half-inverted, and further lowering led to considerable lateral displacement. Displacement in the forward and lateral directions was minimal, implying that spot plowing is suitable for potential application to and verification of the weed population dynamics model in the field. A simple linear matrix model of the population dynamics of annual weeds was proposed, whereby four layers of soil were set to describe tillage and other ecological events. The effect of tillage on weed control was evaluated by the equilibrium reproduction rate allowed to sustain a stable population of weeds. The simulation model showed that alternately changing the depth of spot plowing had a significant effect on controlling weeds of a low seed survival rate, even when some incomplete inversion of the soil slice was taken into account.

Keywords: soil tillage, complete inversion, tillage depth, seed burial

INTRODUCTION

Tillage, one of the most effective methods of physically controlling weeds, has been re-evaluated in the last decade in view of environmental concerns. Several approaches with models of weed population dynamics have been developed to evaluate the effect of tillage on weed control. Cousens and Moss (1990) have introduced the 'Leslie' matrices of probability to express vertical translocation of weed seeds, with the use of tillage and other practices, and have combined them with other biological and environmental parameters to simulate the effect of cultural practices on controlling annual weeds. Sakai *et al.* (1998) have presented a similar model, showing that biannual alternation, compared with no alternation, of the plowing depth depresses the weed population.

Describing the movement of soil induced by tillage is a crucial factor in the model for comparing the effect of specific cultural practices. For example, both Cousens and Moss (1990) and Sakai *et al.* (1998) have measured the probability matrices for plow, cultivator, or harrow at given soil conditions by directly measuring the movement of beads buried in several layers of soil. Colbach *et al.* (2000) and Roger-Estrade *et al.* (2001) have modeled vertical and lateral movements of weed seeds induced by moldboard plowing by introducing 'slivers' or pulverized soil slices to illustrate soil movement in lateral direction, confirming that their describing agrees well with the actual movement of the soil.

The following expressions of the probability matrices $[t_{ij}]$ idealize the function of typical tillage implements. For simplicity, only four layers of the soil are considered, and each element indicates the probability of the soil moving from layer i to layer j.

No tillage is described as Fig. 1a and expressed by following matrix:

$$[t_{ij}] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \ldots(1)$$

A shallow cultivator indicates minimum translocation of soil among the layers, which is also idealized by Equation (1). In the field, not all the soil remains in the same layer, therefore, the diagonal elements vary from 0.50 to 0.84 (Cousens and Moss, 1990), and the rest of the elements are not always zero.

'Complete mixing' is shown in Fig. 1b and idealized as below:

$$[t_{ij}] = \begin{bmatrix} 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & 0.25 & 0.25 & 0.25 \\ 0.25 & 0.25 & 0.25 & 0.25 \end{bmatrix} \qquad \ldots(2)$$

This operation can be presumably accomplished by intensive secondary tillage implement such as rotary harrow, although there is not any report available that actually has measured its probability matrix in the field.

In fact, the matrices for conventional moldboard plowing also indicate the nature of mixing idealized by Equation (2). Contrary to the well-recognized function of surface burial completed by moldboard plows, this expression of uniform redistribution of soil is attributed to the diagonal placement of the inverted slices of soil after plowing (Fig. 1c). However, when a 'skim-coulter' or auxiliary upper moldboard is used to bypass a specific portion of the surface soil and to bury a portion of weed seeds directly into the bottom of the furrow, elements t_{11} and t_{41} are 0.07 and 0.43, respectively (Roger-Estrade *et al.*, 2001), with the plow having certain function of 'inversion' (Fig. 1d).

Although a combination of these cultural practices undoubtedly contributes to weed control, the function of soil inversion should be further explored to obtain enhanced effects of tillage. Since a portion of annual weed seeds do not survive during winter, it would be effective to concentrate the seeds around the bottom of the plowed furrow and to leave them for several winters, without redistributing them among the layers of soil, by inverting the soil slice 180° (Fig. 1e and 1f). This operation is hereinafter referred to as 'complete inversion', as idealized by the following expression:

$$[t_{ij}] = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \qquad \ldots(3)$$

Little attention has been paid to the design of plows for the specific function of complete inversion. Shoji *et al*. (2000) have designed a conventional 360 mm-wide moldboard plow that aims at complete inversion, but it is applicable only to depths of less than 100 mm, as illustrated in Fig. 1f. This is attributed to the unavoidable placement of soil slices diagonally (Fig. 1c) at a large 'aspect ratio' or depth-to-width ratio, regardless of how well the moldboard is designed for conventional plowing involving the lateral displacement of soil. Therefore, as an alternative tillage implement, the 'spot plow' (Shoji, 2001; 2003) is considered here for the complete inversion of soil, and a single bottom prototype is used to explore the possibilities of complete inversion 'on the spot' without lateral displacement of soil.

MATERIALS AND METHODS

The spot plow

A prototype of the spot plow was developed (Fig. 2) and constructed on the base frame of a conventional moldboard plow (SUGANO, QY-141) with a single bottom. Facing forward, it inverted the soil slice clockwise. The working width and depth were 360 mm and 100-180 mm, respectively. Four principal working components were arranged in sequence: front disk coulter, share, short moldboard, and tilted disk coulter. The front disk coulter and the share remained as originally manufactured, while the moldboard and the tilted disk coulter were newly fabricated. The shoe and the landside were removed during the experiment.

The spot plow was designed and tuned to operate at a speed of 1.9 m s^{-1}; the soil slice was lifted and rotated by its own inertia to complete the spot inversion. The cross-section of the soil slice was assumed not to be severely pulverized in the process; soils with root-mats, clay or moisture content such as drained paddy soils, functioning as bonding agents are the target for spot plowing. The soil slice was targeted to receive rotational acceleration from the moldboard and the tilted disk coulter, then to land on its own furrow without being laterally displaced. Therefore, the moldboard rotated the soil slice only up to an angle of 60°, and the length of the bottom from the share point to the rear edge of the tilted disk coulter became as short as 650 mm. The tilted disk coulter was placed with its center aligned with the rear edge of the moldboard at an angle of 8° to the traveling direction. This configuration of the moldboard and the tilted disk coulter was to generate a moment couple to secure the rotation of the soil slice when releasing it. Detailed specifications of the moldboard and the tilted disk coulter are as described by Shoji (2003).

An experiment was conducted to verify the completeness of spot inversion, specifically with a view of assessing the effect of the operating speed. The experimental site was set up in a field in the Food-Resource Education and Research Center (formerly the Experimental Farm) of the Faculty of Agriculture, Kobe University, in Kasai City, Hyogo, Japan (134°52'E, 34°53'N, 53 m in altitude). The soil, with a high clay content, was classified as 'Fine yellow soil' according to the Japanese Soil Taxonomy. The field had not been cultivated for more than five years, and well-developed root-mats of weed roots were dominant only near the surface, with sparse root density at a depth greater than 30 mm. Macro-pores generated by the roots promoted good drainage despite the high clay content; the soil was not very compacted, allowing good penetration and some pulverization upon plowing. The field was mowed approximately one week before the experiment, and the dried residue of the mowed herbage remained on the surface. The cone penetration resistance was 2.7 ± 0.3 MPa at the moisture content of 27.2 ± 1.9% d.b. The prototype was directly hitched to and pulled by a four-wheel-drive tractor (Yanmar FX-22D, 16.5 kW). The operating depth was adjusted mostly between 110 and 130 mm (maximum, 160 mm), and the speed was varied between 0.60 and 1.64 m s^{-1}.

A laser-beam range finder (KEYENCE, LB-1200) mounted on an electro-magnetic linear scale (MTB, Temposonics® LP-SKVM1500) was then used to take cross-sectional profiles (1) of the tilled surface immediately after the operation, (2) with only inverted or half-inverted soil slice or blocks (*i.e.* separated portions of the slice, if any) removed, and (3) with all the tilled soil removed. The inverted soil slice or blocks were facilely distinguished from those not inverted, by the stems and roots of the mowed weeds that still remained on the surface. The forward displacement of soil in the direction of travel was also measured. The surface of the prospective path of the plow was scribed perpendicular to the traveling direction with a stick and painted with lacquer spray. After the plowing, the sides of the furrow were excavated and the painted line on the soil block was uncovered. This simple procedure was practicable because the tilled and inverted soil slices were always relocated in a uniform and consistent manner as with wet plastic soil. Burial and excavation of tracers, therefore, was not attempted here on account of the constancy of plowing and of the readily distinguishable inverted soil slice.

The simulation model

A simulation model was proposed to envisage the effect of spot plow for annual weed control. The model of the population dynamics used in this study is based on that presented by Sakai *et al*. (1998), but mainly focused on tillage; other biological or environmental events are very simplified. For simplicity, only four layers of soil were considered, and tillage depths can be taken from 1 to 4.

$$\begin{Bmatrix} x_{1,n+1} \\ x_{2,n+1} \\ x_{3,n+1} \\ x_{4,n+1} \end{Bmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{pmatrix} \begin{pmatrix} q & 0 & 0 & 0 \\ 0 & q & 0 & 0 \\ 0 & 0 & q & 0 \\ 0 & 0 & 0 & q \end{pmatrix} \begin{pmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{pmatrix} \begin{pmatrix} r & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{Bmatrix} x_{1,n} \\ x_{2,n} \\ x_{3,n} \\ x_{k,n} \end{Bmatrix} \quad \ldots(4)$$

The column vector $\{x_{j,n}\}$ represents the number of seeds of a specific annual weed at soil layer j in the n-th year. The matrices multiplied to the left represent events and transformations in time series. The constant r is total ‘reproduction rate’ during a growing period, including germination, chemical and mechanical control, loss of weed seeds etc. For example, an r = 2 means that when one plant produces 100 seeds in the previous season, 98 are removed by either inability to emerge or weed control practices other than soil tillage during the cropping season. These events occur only at the surface layer, with the rest of the diagonal elements remaining 1. The ‘seed survival rate’ q is the proportion of seeds surviving during each winter, which, for simplicity, is assumed to be independent of the depth. Various other models of reproduction and survival have been reported (*e.g.* Cousins & Moss, 1990; Mohler, 1993; Mohler & Gulford, 1997).

The matrix $[p_{ij}]$ represents deep tillage with the spot plow in autumn, and the matrix $[h_{ij}]$ the seedbed preparation with a rotary harrow in spring when the layers are completely mixed. None of these matrices were actually measured in the field in this study; instead, idealized values were used to explore the strategy of using the spot plow and to compare its practice with conventional moldboard plowing. Tillage depth d_t can be expressed by ‘activating’ the $d_t \times d_t$ elements of the matrix $[t_{ij}]$ (t = p or h). For example, spot plowing and rotary harrowing at operating depths of d_p=3 and d_h=2, respectively, are ideally expressed as:

$$[p_{ij}] = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \ldots(5)$$

and

$$[h_{ij}] = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 \\ 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \ldots(6)$$

That the $[q_{ij}]$ is a diagonal matrix suggests that the timing of such tillage is not important whether done before or after winter, although a change in the order of plowing and harrowing affects the result. It should also be noted that a tillage depth as shallow as one layer denotes no tillage.

In the simulation model, operating depths for plowing and harrowing were varied at given seed survival rate q, and the convergence of the n-th power ($n \to \infty$) of the total product of the matrices *i.e.* $[h_{ij}][q_{ij}][p_{ij}][r_{ij}]$ in Equation (4) was examined. This procedure, unlike assigning a specific initial distribution of seed numbers $\{x_{j,\,0}\}$ (*e.g.* Cousins & Moss, 1990; Sakai *et al.*, 1998; Shoji *et al.*, 2000), was to generalize the property of the model by avoiding year-by-year calculation of the distribution of the seeds. The 'equilibrium reproduction rate' $r_{\max}$ was defined as the reproduction rate r that allowed for a constant population in the model. In other words, the greater the $r_{\max}$ allowed, the less weed control required during the cropping season *i.e.* the greater the effect of off-season tillage on annual weed control. The $r_{\max}$ is implicitly obtained under the condition that for the following eigen equation, eigenvalues λ are present such that:

$$\left.\begin{array}{l}[h_{ij}][q_{ij}][p_{ij}][r_{ij}]\{x\} = \lambda\{x\} \\ |\lambda_{\max}| = 1\end{array}\right\} \quad \ldots(7)$$

where $\{x\}$ is the eigenvector.

The value of winter survival rate q was set variously at 0.7, 0.5, and 0.25, as reviewed by Mohler (1993). The depth of rotary harrowing was set shallower than that of plowing, especially that harrowing deeper than plowing nullifies the effect of plowing by equally distributing the seeds throughout the layers. To compare the effect of spot plowing with that of conventional moldboard plowing, the probability matrix of Cousens and Moss (1990) was also used in the simulation model.

Indeed, it is difficult to obtain an exact matrix of complete inversion such as in Equation (3) or (5). Some seeds on the surface assumed to be buried in the furrow may eventually move to other layers during the plowing because of incomplete inversion or of the existence of macro-pores in the soil slice. 'Partial mixing rate' f was introduced to represent the degree of incomplete inversion, where a portion was assumed to be equally redistributed to other layers. For example, spot plowing at an operating depth of d_p=3 under f = 0.12 is expressed as:

$$[p_{ij}] = \begin{bmatrix} f/2 & f/2 & 1-f & 0 \\ f/2 & 1-f & f/2 & 0 \\ 1-f & f/2 & f/2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0.06 & 0.06 & 0.88 & 0 \\ 0.06 & 0.88 & 0.06 & 0 \\ 0.88 & 0.06 & 0.06 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \ldots(8)$$

RESULTS AND DISCUSSION

Performance of the spot plow

The operating speed of the plow was an important factor affecting complete spot inversion of the soil slice, since the rotation of the soil slice is dependent on its own inertia once it is released behind the plow. At an operating speed of less than 30% of the designated speed, a considerable portion of the soil on the side of the tilted disk coulter was not inverted and remained in place (Fig. 3a) despite the absence of residues or weeds from the surface, implying that the portion was not sufficiently accelerated either in a vertical or a rotational direction and that only the portion originally located on the left side was overly accelerated by the moldboard to cause considerable displacement to the right. Operations at such low speeds sometimes resulted in the whole portion reverting to its original position without being rotated at all.

As the speed was increased to over 60% of the designated speed, the soil was tilled throughout the whole working width, and the finished surface appeared completely 'spot plowed' without residues or weeds on the tilled surface, and particularly, without any visible lateral displacement of soil (Fig. 3b). Careful excavation and observation, however, revealed incompletely inverted portions remaining (Fig. 4b), although they were displaced to the left of the furrow, unlike the outcome shown in Figure 3a. The explanation of this phenomenon is that the portion on the right-hand side before the operation (Fig. 4c, upper panel) was lifted and moved to the left, but landed earlier than anticipated for the lack of inertia and remained half-inverted on the left-hand side (Fig. 4c, lower panel). This indiscernible incomplete inversion, despite the complete 'spot plowed' appearance, was similar to the outcome shown in Figure 3b. Operating at a speed of 1.6 m s^{-1} (86% of the designated speed) however, did not show any more incomplete inversion associated with the lack of operating speed (Fig. 5).

The displacement of soil in the forward direction was minimal, 50-90 mm (Fig. 6). The depth had no effect, but the displacement gradually increased with the speed. This small amount of forward displacement is attributed to the structure that ensures the release of the soil from the plow, which is credited to the shortened moldboard and the enhanced interaction of the tilted disk coulter with the soil slice or blocks. The result is comparable to the one of measurements with conventional tillage tools. For example, Nichols and Reed (1934) have demonstrated forward displacement of about 400 mm on average and up to 800 mm with a conventional moldboard plow 450 mm wide.

Effect of spot plowing on weed control based on the simulation model

Table 1 shows equilibrium reproduction rate $r_{\max}$ for different of tillage depths d_p and d_h under various seed survival rate q and partial mixing rate f, where the greater the value of $r_{\max}$, the more effective the tillage on weed control. Simple tillage with conventional moldboard plow ($d_p = 4$, $d_h = 1$ in the last row of the table) showed a good control, because such plowing involves both mixing and inversion of soil. The $r_{\max}$ decreased as the depth of rotary harrowing (*i.e.* equal redistribution of seeds) increased.

On the other hand, spot plowing at a fixed depth without rotary harrowing ($d_p = 1$, 2, 3 and 4; $d_h = 1$) did not contribute to weed control as much as conventional plowing did, as this procedure simply delays the germination of seeds by burying and turning them up over a period of two years. Therefore, the allowable $r_{\max}$ is exactly the square of that for no tillage ($d_p = 1$, $d_h =1$), regardless of the depth of the complete inversion ($d_h = 2$, 3 and 4). The $r_{\max}$ increased as the depth of rotary harrowing increased ($d_p = 3$, $d_h =2$; $d_p = 4$, $d_h = 2$ and 3), indicating that certain mixing of soil should be included with spot plowing to depress weed population as with conventional plowing. Nevertheless, setting the same depths for rotary harrowing and for plowing ($d_p = d_h$) again lowered $r_{\max}$, since this equal-depth setting is equivalent to omitting the plowing, which is readily indicated by the product $[h_{ij}][p_{ij}]$ becoming exactly $[h_{ij}]$. With the depth of plowing fixed each year, the effect of complete inversion on weed control was not significantly different from conventional moldboard plowing, and in some cases, the weed control was even reduced.

The depth of spot plowing was altered every two years (d_p = 2-3, 3-4) to retain the reproduced seeds as long as possible in the soil by maximizing the benefit of complete inversion for the least redistribution of seeds. Significantly large $r_{\max}$ was obtained even when the depth of spot plowing was not set at the maximum. The effect of depth alternation on weed control was more evident with a low seed-survival rate q, suggesting the preservation of such short-life seeds as long as possible in the soil; however, the sharp suppression of weed population with simple spot plowing (d_p = 3-4, d_h = 1) was nullified by the equal redistribution with rotary harrowing (d_p = 3-4, d_h = 2). Therefore, contrary to the fixed-depth spot plowing, extremely shallow cultivation or tillage tools that result in little redistribution would be preferable for secondary tillage within this specific scheme of the cultural practice of annual weed control.

'Partial mixing' or incomplete inversion lowered the equilibrium reproduction rate $r_{\max}$ especially for lower seed survival rate q (Table 1, f = 0.1 and 0.2). The explanation for this result is that that exact placement of fresh seeds into the furrow bottom was disturbed by the slight mixing of soil that allowed some seeds to be redistributed to the surface layers for germination. In case of significant redistribution or practically the failure of the inversion (f = 0.2), the $r_{\max}$ for spot plowing (d_{p} = 3-4; q = 0.25) reached the same level as that with conventional plowing. Nonetheless, the partial mixing rates designated for the simulation model here are still estimated too high. For example, Shoji and Kurstjens (2006) have reported a mixing rate of less than 0.06 for successful inversion of a triangular soil slice, and the presence of partially mixed fresh seeds is mainly attributed to the roll-in function of disk coulters.

Table 1 demonstrates that when the tillage depth of spot plowing is strategically altered and some partial mixing of soil is assumed at a practical level, the effect of spot plowing on annual weed control is estimated to be significantly high for seed species of low survival rate and to be at the same level as with conventional moldboard plowing for species of high survival rate.

Perspective for future development

Minimal displacement of soil in both forward (Fig 6) and lateral (Fig 3b) directions is beneficial in applying a simple model of population dynamics such as used in this study. As the model involves the translocation of soil and weed seeds only in the vertical direction, dispersal of soil in other directions becomes a source of potential error in the model. For example, Colbach *et al.* (2000) and Roger-Estrade *et al.* (2001) have illustrated lateral movement of soil induced by conventional moldboard plowing, indicating that that soils located at different depths are transported to different distances in the lateral direction. Therefore, the spot plow with minimal soil displacement is suited for potential application to and validation of the population dynamics model in the field.

Nonetheless, more development and studies are needed to verify the adaptability of the spot plow to various operating conditions, so that the prospected effect on weed control discussed in the simulation model could be verified in the field. For example, a greater operating depth should be tested, especially that a depth of more than 160 mm was not feasible in this study due to the power of the tractor. Although there is a limitation in the aspect ratio of around 2.0 (*i.e.* the depth of 180 mm for the current design) from the geometrical point of view of the interference of the soil slice with the untilled wall of soil (Shoji, 2001), exploring the possibility of deep spot plowing would widen the degree of freedom in strategies of weed control. For such a specific purpose, a symmetric design for inverting a pair of slices inward (Fig. 1e) is one of the possible measures. In case thick soil slices are left facing with each other (chain line in Fig. 1e), gravity or supplementary devices settle the slices to accomplish complete inversion on the spot. The spot plow should also be tested in and adapted for sandy or fragile soils to make possible the application of complete inversion and depth alternation to various types of fields for enhanced effect of tillage techniques on weed control.

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REFERENCES

Colbach N., Roger-Estrade J., Chauvel B. and Caneill J. 2000. Modelling vertical and lateral seed bank movements during moldboard ploughing. *European Journal of Agronomy* **13**, 111-124.

Cousens R. and Moss S.R. 1990. A model of the effects of cultivation on the vertical distribution of weed seeds within the soil. *Weed Research* **30**, 61-70.

Mohler C.L. 1993. A model of the effects of tillage on emergence of weed seedlings. *Ecological Applications* **3**, 53-73.

Mohler C.L. and Galford A.E. 1997. Weed seedling emergence and seed survival: separating the effects of seed position and soil modification by tillage. *Weed Research* **37**, 147-155.

Nichols M.L. and Reed I.F. 1934. Soil dynamics: VI. Physical reaction of soils to moldboard surfaces. *Agricultural Engineering* **15**, 187-190.

Roger-Estrade J., Colbach N., Leterme P., Richard G. and Caneill J. 2001. Modelling vertical and lateral weed seed movements during moldboard ploughing with a skim-coulter. *Soil and Tillage Research* **63**, 35-49.

Sakai K., Tani S. and Takai M. 1998. [A model of effects of reciprocally changed plowing depth on weed seed population.]. *Journal of the Japanese Society of Agricultural Machinery* **60**(6), 19-26 (in Japanese with English abstract).

Shoji K., Yamamoto H. and Horio H. 2000. Development of a plow for complete inversion and effective weed control. *Proceedings of the 15th International Soil and Tillage Research Conference*, Fort Worth, USA, CD-ROM.

Shoji K. 2001. Design of a model 'spot plough' for inversion of soil slice within the furrow. *Journal of Agricultural Engineering Research* **79**, 283-297.

Shoji K. 2003. Field performance of 'spot plough'. *Proceedings of the 16th International Soil and Tillage Research Conference*. Brisbane, Australia, 1120-1126.

Shoji K. and Kurstjens D.A.G. 2006. Triangle strip plough in precise guidance of controlled traffic farming system combines the advantages of mouldboard ploughing and conservation tillage. *Proceedings of the 17th International Soil and Tillage Research Conference*, Kiel, Germany, CD-ROM.

Table 1. Equilibrium reproduction rate $r_{\max}$ allowed of annual weed simulated in terms of the tillage depths d_p, d_h , seed survival rate q and partial mixing rate f

d_p [a)]	d_h [a)]	q	$r_{\max}$			q	$r_{\max}$	q	$r_{\max}$		
			f=0	f=0.1	f=0.2		f=0		f=0	f=0.1	f=0.2
1 [b)]	1 [b)c)]		1.4				2.0		4.0		
2	1 [b)]		2.0				4.0		16		
	2 [c)]		1.8				3.0		7.0		
3	1 [b)]		2.0	2.2	2.4		4.0		16	16	15
	2		2.6	2.5	2.5		5.8		26	23	18
	3 [c)]		2.2				4.0		10		
4	1 [b)]		2.0	2.3	2.6		4.0		16	17	7
	2	0.7	3.0	3.2	3.2	0.5	7.0	0.25	31	27	24
	3		3.2	3.4	3.3		8.0		38	32	26
	4 [c)]		2.7				5.0		13		
2 - 3 [d)]	1 [b)]		2.9	2.9	2.9		8.0		64	30	20
3 - 4 [d)]	1 [b)]		4.1	3.9	3.6		16		256	51	32
	2		3.0	3.3	3.2		7.0		31	30	25
4 [e)]	1 [b)]		3.4				8.1		36		
	2		3.5	NA	NA		8.0		29	NA	NA
	3		3.1				6.2		17		

a) Depths of spot plowing and rotary harrowing expressed in terms of the number of layers to be tilled.
b) Depth 1 for d_p or d_h denotes no tillage.
c) Depths d_p=d_h: complete mixing by the harrowing that exhibits no effect of plowing.
d) Depth of spot plowing alternately changed every two years under the same values of other parameters.
e) Probability matrix for conventional moldboard plowing (Cousens and Moss, 1990) was used.

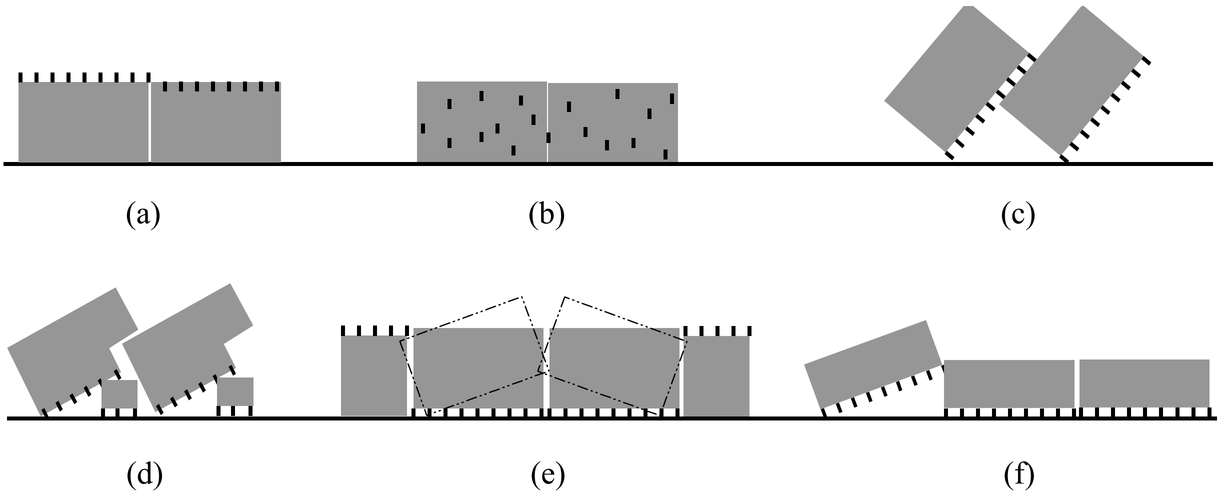


Fig. 1. Movement of soil induced by typical tillage practices. (a), no or very shallow tillage; (b), complete mixing with harrows (c), diagonal arrangement of soil slices at a large operating depth with a conventional moldboard plow; (d), certain inversion by bypassing a portion with skim coulter mounted on moldboard plow; (e), complete inversion with a 'spot plow'; (f), complete inversion at a small operating depth achievable with conventional plow.

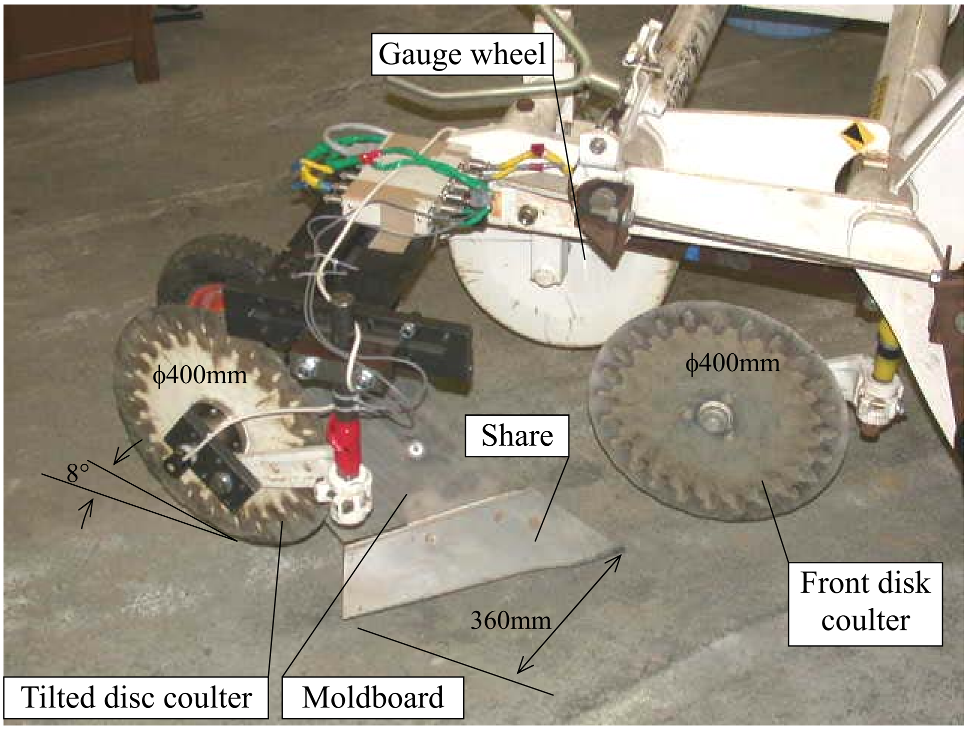


Fig. 2. Overview and principal working components of the spot plow.

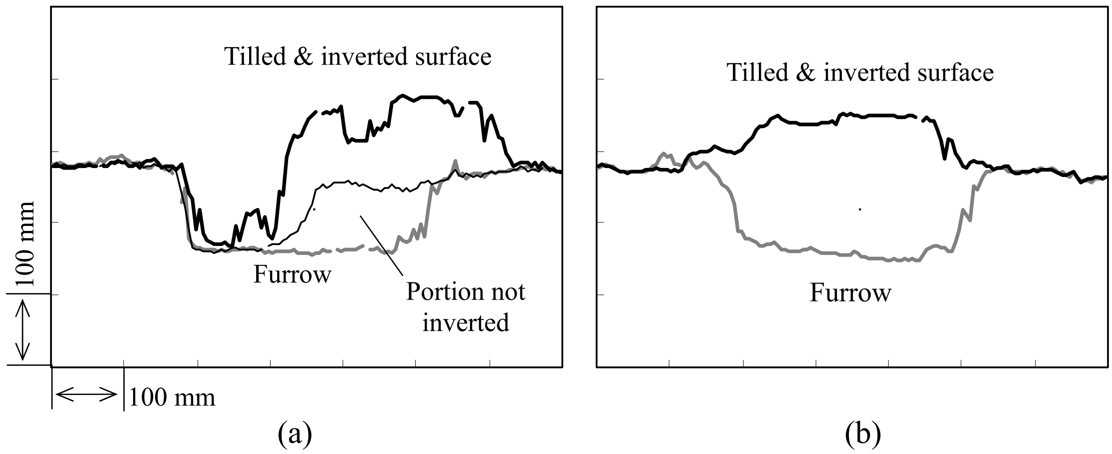
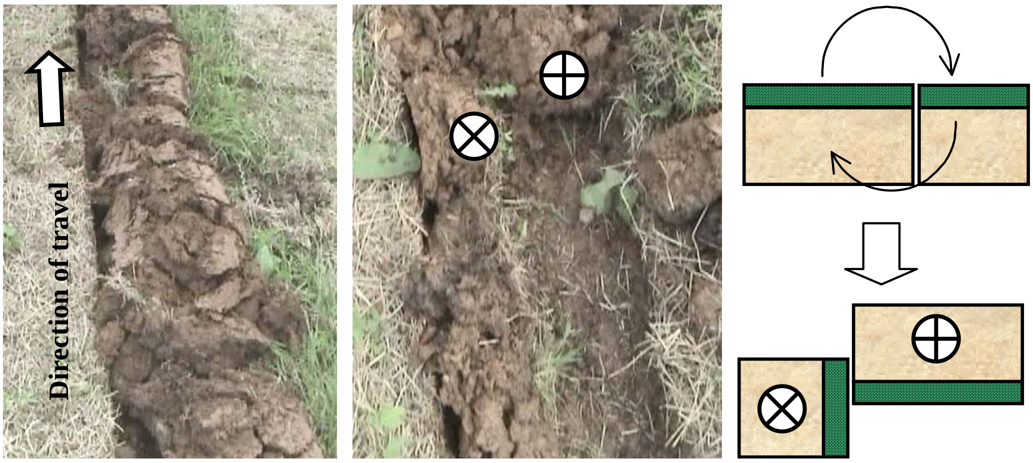


Fig. 3. Examples of cross-sectional profiles. (a), speed 0.6 m s^{-1}, depth 126 mm; (b), speed 1.2 m s^{-1}, depth 111 mm.



(a) (b) (c)

Fig. 4. Indiscernible incomplete inversion of soil; speed 1.4 m s^{-1}, depth 120 mm. (a), appearance after operation; (b), partial excavation showing a half-inverted portion on the left-hand side; (c), conceivable movement of the soil slice and its splitting into two blocks that resulted as (b).

Fig. 5. Complete inversion of soil achieved at a speed of 1.6 m s^{-1} and a depth of 115 mm.

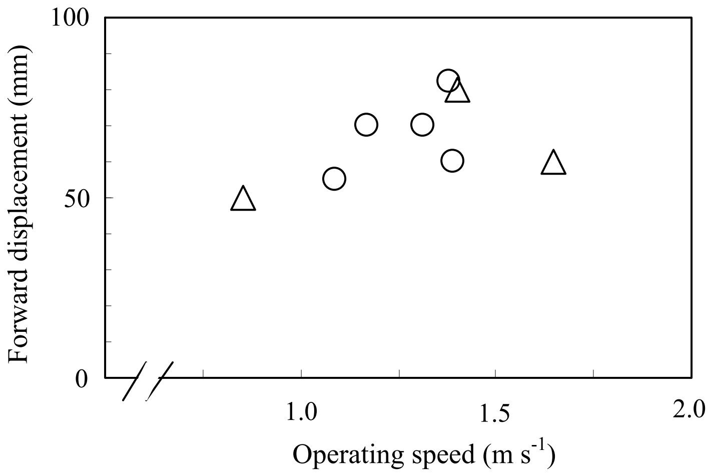


Fig. 6. Forward displacement of soil. (Δ), average depth 111 mm; (○), average depth 127 mm.

Figure Legends

Table 1. Equilibrium reproduction rate $r_{\max}$ allowed of annual weed simulated in terms of the tillage depths d_p, d_h , seed survival rate q and partial mixing rate f

Fig. 1. Movement of soil induced by typical tillage practices. (a), no or very shallow tillage; (b), complete mixing with harrows (c), diagonal arrangement of soil slices at a large operating depth with a conventional moldboard plow; (d), certain inversion by bypassing a portion with skim coulter mounted on moldboard plow; (e), complete inversion with a 'spot plow'; (f), complete inversion at a small operating depth achievable with conventional plow.

Fig. 2. Overview and principal working components of the spot plow.

Fig. 3. Examples of Cross-sectional profiles. (a), speed 0.6 m s^{-1}, depth 126 mm; (b), speed 1.2 m s^{-1}, depth 111 mm.

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