

# Assessment of tillage erosion by mouldboard plough in Tuscany (Italy)

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## Abstract

This study was designed to characterise the soil translocation effect induced by mouldboard ploughing with an implement traditionally used in the Tuscany region (Central Italy). We discuss the results of a set of field experiments performed to measure soil displacement along slopes of varying gradient in different directions and at several depths of tillage. Using the Soil Erosion by Tillage (SETi) model, soil translocation patterns for different tillage scenarios were analysed, with special attention paid to the effects of the direction and depth of tillage on the extent and spatial pattern of soil movement. The lateral slope gradient  $S_P$  and tillage depth  $D$  were found to be the dominant controlling factors for total soil displacement. The effect of the slope gradient in a direction parallel to tillage  $S_T$  was much less pronounced. These findings reveal the importance of the asymmetric nature of the soil movement produced by mouldboard ploughing and the predominant effect of the lateral displacement  $d_P$  on the actual trajectory of soil motion. Results demonstrate that spatial patterns of soil redistribution due to mouldboard ploughing are highly variable and depend on the particular characteristics of the implement used. This dependence is so strong that maximum downslope soil translocation can occur during both, contour tillage or up-down tillage. For this particular mouldboard plough, maximum downslope soil transport took place at a tillage direction ca.  $70^\circ$  and not when tillage was conducted along the steepest slope direction ( $0^\circ$ ). These findings highlight the potential of the combined approach applied. The physically based SETi model can be properly calibrated using a relatively limited dataset from field experiments. Once calibrating, the SETi model can then be used to generate synthetic tillage translocation relationships, which can predict the intensity and spatial pattern of soil translocation over a much wider range of tillage scenarios than the particular experimental conditions, in terms of topography complexity (slope gradients and morphology) and the direction and depth of tillage. These synthetic relationships are useful tools for evaluating strategies designed to reduce tillage erosion.

*Keywords:* Tillage erosion; Tillage translocation; SETi model; Field experiments; Modelling; Metal tracers; Electromagnetic probe

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## 1. Introduction

Tillage has been recognised as a cause of intense landscape modification and as a major source of soil erosion and redistribution along hillslopes (Guiesse and Revel, 1995; Govers et al., 1999; Torri et al., 2002). The first documented experimental study in which soil translocation by tillage was evaluated dates back to the 1940's (Mech and Free, 1942). Despite profound evidence of soil translocation processes, it was only in the 1990s that systematic research on this topic began (e.g., Lindstrom et al., 1990, 1992; Govers et al., 1994; Quine et al., 1994; Lobb et al., 1995).

The practice of mouldboard ploughing warrants particular attention, since it is the most common method of primary tillage used in conventional agriculture systems. Further, it has been reported that mouldboard ploughing leads to high rates of soil transport and erosion (e.g., Govers et al., 1994; Gerontidis et al., 2001). The mouldboard plough causes the detachment and movement of the entire topsoil layer (i.e., the plough layer), generally at a uniform depth of 0.24–0.40 m, but in extreme cases such as those of cropped areas of clayey soils in the Tuscany region, tillage depth frequently surpasses 0.50 m. Of particular interest are the experimental works related to the use of the mouldboard plough by Lindstrom et al. (1990, 1992), Revel et al. (1993), Govers et al. (1994), Lobb et al. (1995, 1999), De Alba (1998, 2001), Van Muysen et al. (1999, 2002), Torri and Borselli (2002) and Gerontidis et al. (2001).

The morphology (slope gradient, curvature) and characteristics of tillage operations (tillage implement, and the direction, speed and depth of tillage) appear to be the main factors controlling soil redistribution over a slope. Soil displacement is proportional to the gradient of the local slope, while net rates of soil loss or gain are related to the morphology and curvature of the slope, i.e., that erosion prevails on convexities or shoulders and deposition prevails in concavities or hollows (e.g., Lindstrom et al., 1992; Govers et al., 1999). In an independent manner, De Alba (2001) and Torri and Borselli (2002) recently demonstrated that soil displacement due to mouldboard ploughing is not only affected by the local steepest slope gradient but also by the relative orientation of the slope aspect with respect to the tractor's direction of motion. These

authors argue that to accurately describe soil translocation, the actual trajectory of soil movement needs to be determined along with the total displacement distance. Soil displacement along the steepest slope direction is only one component of the soil motion trajectory, and in most cases it is not the dominant direction.

Tillage experiments are the most basic source of data for establishing relationships between soil displacement due to tillage and control factors such as the type of implement, the slope gradient, the depth and speed of tillage, etc. However, variables that can be inferred from experimental data are constrained by the limited experimental conditions under which they were obtained; this restriction being greater, the smaller the experimental dataset. For the combined approach used in this paper, experimental data were used to calibrate the physically based Soil Erosion by Tillage (SETi) model, to generate more general soil translocation equations. These equations could then be used to describe the results and extrapolate them to a broader range of tillage scenarios than those of the experimental conditions.

The general objective of the present study was to characterise the translocation effects of mouldboard ploughing using a type of instrument of widespread use in Tuscany (Central Italy). The results of a set of field experiments, performed to measure soil displacement along different slope gradients in different directions and at different depths of tillage, are discussed. Soil translocation patterns in different tillage scenarios were analysed using the SETi model, with special emphasis placed on the effect of the direction and depth of tillage on the extent and spatial pattern of soil movement. Finally, we discuss some of the practical implications of the experimental and theoretical findings in evaluating possible tillage patterns that might reduce tillage erosion.

## 2. Methods

The study area was located at the S. Elisabetta Experimental Centre, Vicarello (Volterra) in the central hilly region of Tuscany (43°27'N, 11°30'E, 151.5 m above mean sea level). Its climate is Mediterranean, sub-humid with a mean annual precipitation of 678 mm (1954–1996). The soil of

the experimental site is a Vertic Xerorthent (Soil Survey Staff, 1975), developed over Pliocene clayey marine deposits. The topsoil has an average clay content of 45%, a bulk density of  $1.4\text{--}1.5\text{ Mg m}^{-3}$  and an organic carbon content of 1%. Agronomical management of this experimental site is that typical to the central Tuscany area. The dominant cropping system is cereal and forage rotation. Cereal cultivation is usually alternated with the growth of forage species, mainly alfalfa, every two years. Characteristic tillage operations are mouldboard ploughing to a depth of 0.35–0.5 m, followed by disking before cereal or alfalfa sowing. The area has a rolling morphology with frequent steep slopes of up to 45% gradient; fields of up to 40% slope being commonly ploughed. In these extreme conditions, it is common practice to conduct tillage along a direction oblique to the maximum slope direction. Interviews with local farmers revealed that this tillage pattern is widespread and based on empirical observations. The oblique direction of tillage allows farmers to reduce the time of tillage operations, reduce fuel consumption and achieve maximum movement of soil clods and soil loosening.

### *2.1. Field experiments designed to quantify soil translocation due to tillage*

Soil displacement due to mouldboard ploughing was determined in 19 field experiments. The tillage equipment used was similar to the most widespread in the study area. Tillage operations were conducted using a tracked tractor with a mouldboard plough with a single deep-tillage bottom 45 cm width. In the experimental hillslope, a detailed survey was performed to locate each plot and determinate its local slope gradient and aspect. The experimental plot had an area of ca.  $10\text{ m}^2$ , in which an average number of 152 metallic tracers were installed buried in the soil. The tracers were placed along eight microwells, 45 cm depth and 2 cm of diameter, at a vertical distance of 2.5 cm from each other. The space between tracers was filled with mud such that they became incorporated into the soil mass. Each tracer was identified by an alphanumeric code. The position of each microwell and tracer was recorded with reference to a local system of Cartesian coordinates ( $x$ ,  $y$ ,  $z$ ) using a Total Station.

For each tillage experiment, we defined the tractor trajectory for the tillage operation and measured the corresponding counter-clockwise angle ( $\omega$ ) between the slope aspect and the tillage direction. Before each experiment, tillage depth was established outside the experimental plot. During tillage, the speed of the tractor was kept constant at an average of between 1.1 and  $1.3\text{ m s}^{-1}$ . Tillage speed was measured by recording the total time needed to go over a given control distance within the plot. The starting soil conditions were: mean soil moisture 12% and mean soil bulk density  $1.5\text{ Mg m}^{-3}$ . A median clod diameter of 0.1 m was calculated by analysing clod size distribution in the topsoil after tillage using a standard sieving method and around 50 kg of soil mass. Table 1 describes the conditions for all the experimental plots including, slope gradient, direction and depth of tillage and the field method used to measure tracer displacement: (1) the excavation method or (2) the low-induction electromagnetic probe method (EM38).

Eleven field experiments were conducted using the excavation method (Fig. 1). These experiments involved recovering the tracers after tillage using a metal detector. The tracers were then dug out and identified. The final position of each tracer was recorded according to a local coordinates system. The difference between the initial and final position of each tracer was used to calculate total tracer displacement and the displacement components in the directions  $x$ ,  $y$  and  $z$ . For the whole set of experiments, the average proportion of tracers recovered was always greater than 90%.

The EM38 electromagnetic probe (Geonics Ltd.) was used in a further eight experiments. This method is based on mapping electromagnetic anomalies induced by the metal tracers incorporated into the soil. The EM38 probe measures topsoil electrical conductivity by inducing a secondary magnetic field. The experimental protocol used is described in detail in Borselli and Torri (2001). The set-up of the plots for the experiments is similar to that described above for the excavation method except that tracer density is double. In each plot, 304 tracers were placed along two parallel vertical lines of microwells as indicated in Fig. 2. Unlike the former method, the size and direction of movement is given by the difference between the positions of the centre of mass of the entire set, or “cloud”, of tracers before and after the

Table 1

Overview of the experimental setup for the mouldboard experiments

Plot	Slope gradients (%)			Tillage direction, $\omega$ (°)	Depth of tillage (m)	Field method
	$S_{max}$	$S_T$	$S_p$			
1	4.0	-3.9	-1.0	15	0.42	Excavation method
2	34.0	-34.0	0.0	0	0.42	Excavation method
3	25.4	-23.9	-8.7	20	0.42	Excavation method
4	16.7	-16.6	-1.5	5	0.42	Excavation method
5	13.1	-12.8	-2.7	12	0.27	Excavation method
6	4.6	-4.5	-0.8	10	0.42	Excavation method
7	34.0	-34.0	0.0	0	0.27	Excavation method
8	25.4	-25.0	-4.4	10	0.27	Excavation method
9	16.7	-16.4	-2.9	10	0.27	Excavation method
10	13.1	-13.1	-1.1	5	0.42	Excavation method
11	4.6	-4.6	0.4	355	0.27	Excavation method
12	23.0	-19.1	-12.9	34	0.27	Electromagnetic probe
13	37.0	-34.3	-13.9	22	0.27	Electromagnetic probe
14	27.0	-21.6	-16.2	37	0.27	Electromagnetic probe
15	12.0	-5.8	-10.5	61	0.27	Electromagnetic probe
16	9.0	-5.2	-7.4	55	0.45	Electromagnetic probe
17	20.0	-3.5	-19.7	80	0.35	Electromagnetic probe
18	25.0	-10.6	-22.7	65	0.28	Electromagnetic probe
19	39.0	-16.5	-35.3	65	0.35	Electromagnetic probe

$\omega$ , Angle (counter clockwise) between tillage direction and slope aspect,  $S_{max}$ , maximum slope gradient;  $S_T$ , slope gradient in the direction of tillage;  $S_p$ , slope gradient in the direction perpendicular to tillage.

tillage operation, thus there is no need to individually identify each tracer. A rigid wooden frame (Fig. 2) was used as a reference for the local electromagnetic measurements. The main advantage of this method is that it is quick to perform and avoids disturbing the soil surface. The method is just as accurate, its maximum estimation error being 0.1 m for the position of the tracer cloud centre of mass (Borselli and Torri, 2001). Initial soil conditions for the

experiments were similar to those used for the excavation method.

## 2.2. Estimating soil translocation using the Soil Erosion by Tillage model

The Soil Erosion by Tillage model developed by Torri and Borselli (2002) is a physically based model that simulates the 3D behaviour of the transported soil.

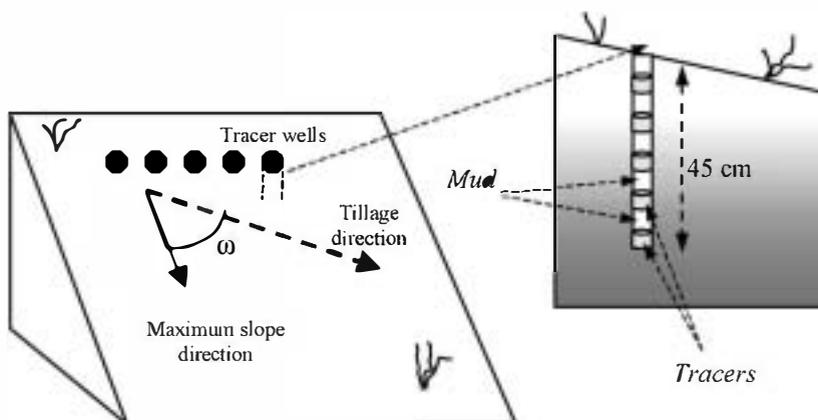


Fig. 1. Site setup of an experimental plot using metal tracers.

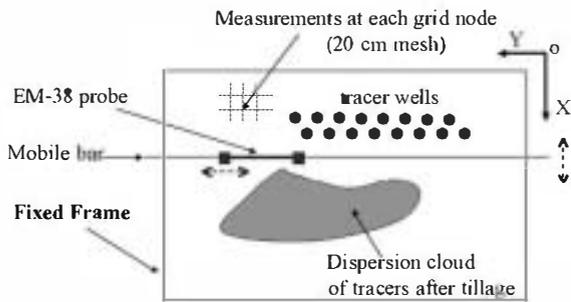


Fig. 2. Experimental setup for measuring the cloud of tracers left after tillage using an EM38 electromagnetic probe. The size of the wooden frame used for the Vicarello experiments was 3.5 m × 3.5 m.

A flow-chart describing the simulation model is provided in Fig. 3. The model identifies three different phases of soil motion as follows:

- (1) *Drag phase*: movement of soil in contact with the tillage implement. The only significant force is the drag exerted by the tillage device.
- (2) *Jump phase*: soil clouds projected by the tillage implement are free to fall under the effects of gravity and of their velocity at the time of ejection.

- (3) *Rolling phase*: the clouds roll (or slide) for a while under the effects of gravity, resistance and their velocity immediately after the jump phase (or the drag phase in the absence of jump).

The different control factors and algorithms governing each of these motion phases are described in detail in Torri and Borselli (2002). The SETi model is coded into a computer program in a MathLab<sup>®</sup> environment. The input data are the average mass and diameter of the soil clods, the tillage implement characteristics, the tractor speed and the tillage direction with respect to the slope aspect. The implement characteristics are related to the size and shape of the instrument, and are formulated in terms of the directions in which the soil is ejected from the mouldboard blade: the overturning lateral direction ( $\alpha$  angle) and the vertical angle of soil ejection ( $\phi$  angle). The outputs of simulation are equations describing the soil displacements produced during each motion phase as functions of the maximum slope gradient and direction of tillage ( $\omega$  angle) for three different directions of soil movement: (a) along the maximum slope, (b) across the slope and (c) in a vertical direction.

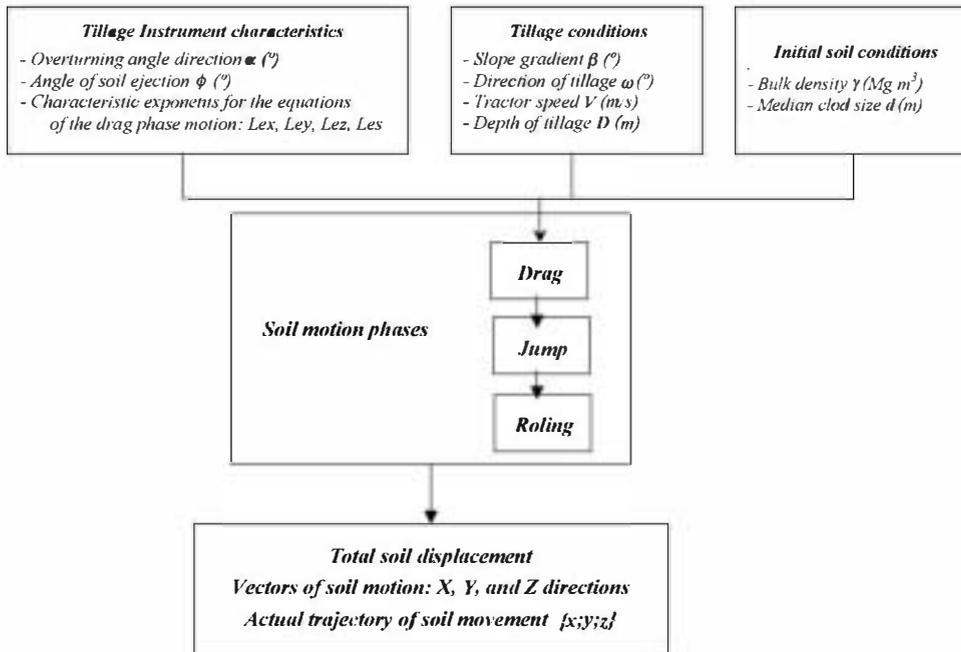


Fig. 3. Flowchart of the Soil Erosion by Tillage (SETi) model.

### 3. Results and discussion

#### 3.1. Soil displacement versus tillage direction and topography

There are scarce published experimental data on soil displacement during tillage in a direction oblique to the direction of the steepest slope. The data available are practically only related to tillage conducted up- and downslope or across the slope (contour tillage). In contrast, our experiments were mainly performed for directions of tillage oblique to the slope aspect. In most cases, the tillage direction ( $\omega$ ) was much greater than  $5^\circ$ ; the tillage direction closest to an across-slope direction being  $80^\circ$ . Following the convention used by Lindstrom et al. (1990), negative signs were assigned to the slope gradients  $S_T$  (slope gradient in the direction parallel to tillage) and  $S_P$  (slope gradient in the direction perpendicular to tillage) when the tractor moved downslope (i.e.,  $S_T < 0$ ) or when the soil was overturned laterally downwards (i.e.,  $S_P < 0$ ), while positive signs were assigned in the opposite cases. Fig. 4 shows a scatter plot of the slope combinations of  $S_T$  and  $S_P$  used in the field experiments.

The results of the field experiments are outlined in Table 2. We performed a statistical analysis of covariance (ANCOVA) to check for possible differences in the results derived from the two methods of measuring metal tracer displacement in the field experiments. In this analysis, the measurement method was the control factor, total soil displacement

$d$  was the dependent variable, and  $S_P$  and  $S_T$  were the covariables. It was shown that the two methods did not differ significantly ( $F(1.15) = 0.40$ ,  $p < 0.54$ ) and consequently the two experimental datasets were analysed as a single set irrespective of the method used to estimate soil displacement.

Table 3 shows the correlations between average soil displacements (forward in the direction of tillage  $d_T$ , in a perpendicular direction to that of tillage  $d_P$  and along the actual trajectory of soil movement  $d$ ) and the slope gradients (in the direction of steepest slope  $S_{max}$  – absolute value – parallel to tillage  $S_T$  and perpendicular to tillage  $S_P$ ). As expected, the regression analysis revealed a weak but significant direct linear relationship between total soil displacement  $d$  and the steepest slope gradient  $S_{max}$  ( $r = 0.39$ ;  $n = 19$ ;  $P$ -value  $< 0.05$ ). In contrast,  $d$  showed significant inverse correlation with the lateral slope  $S_P$  ( $r = -0.53$ ;  $n = 19$ ;  $P$ -value  $< 0.05$ ) but no significant association with the forward slope  $S_T$ . In a parallel similar,  $d$  was significantly correlated with the lateral displacement  $d_P$  ( $r = 0.92$ ;  $n = 19$ ;  $P$ -value  $< 0.05$ ) but not with the forward displacement  $d_T$  (Fig. 5).

With regard to the two orthogonal components of soil movement,  $d_T$  and  $d_P$ , Fig. 4 shows models of significant correlation between soil displacement and slope gradient.  $d_T$  showed a significant inverse relationship with the slope gradient  $S_T$  ( $r = -0.70$ ;  $n = 19$ ;  $P$ -value  $< 0.05$ ). Lateral displacement,  $d_P$ , showed a significant inverse relationship with the slope gradient  $S_P$  ( $r = -0.63$ ;  $n = 19$ ;  $P$ -value  $< 0.05$ ). Consequently, greater lateral soil displacement occurs

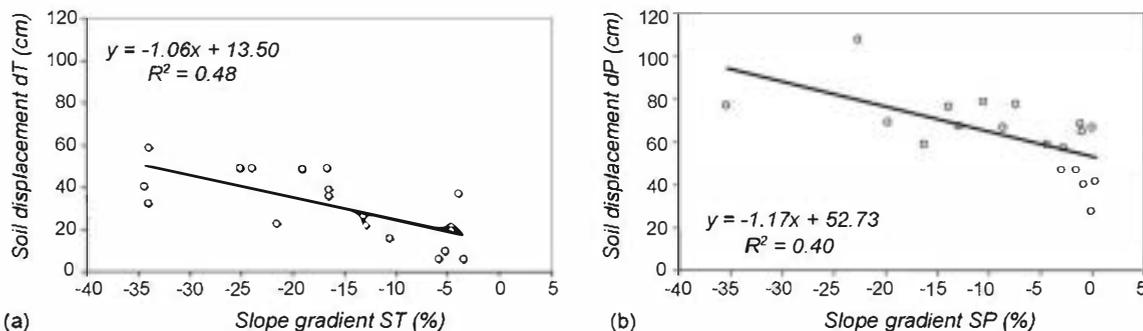


Fig. 4. Models of regression between soil displacement and slope gradient: (a)  $d_T$  vs.  $S_T$ ; (b)  $d_P$  vs.  $S_P$ .  $d_T$ , soil displacement in the tillage direction;  $d_P$ , soil displacement in the direction perpendicular to tillage;  $S_T$ , slope gradient in the direction of tillage;  $S_P$ , slope gradient in the direction perpendicular to tillage.

Table 2

Summary of the experimental results

Plot	Slope (%), $S_{max}$	Tillage direction, $\omega$ (°)	Soil displacement (m)						
			$d$ -down	S.D.	$d$ -across	S.D.	$d$	$d_T$	$d_P$
1	4	15	0.53	0.28	-0.53	0.25	0.75	0.37	0.65
2	34	0	0.59	0.41	-0.66	0.37	0.88	0.59	0.66
3	25.4	20	0.68	0.48	-0.46	0.23	0.82	0.49	0.66
4	16.7	5	0.52	0.35	-0.42	0.29	0.67	0.49	0.47
5	13.1	12	0.33	0.11	-0.51	0.41	0.61	0.21	0.57
6	4.6	10	0.27	0.15	-0.36	0.35	0.45	0.21	0.40
7	34	0	0.32	0.19	-0.27	0.11	0.42	0.32	0.27
8	25.4	10	0.58	0.28	-0.49	0.38	0.76	0.49	0.58
9	16.7	10	0.46	0.2	-0.39	0.19	0.60	0.39	0.46
10	13.1	5	0.32	0.13	-0.66	0.36	0.73	0.26	0.68
11	4.6	355	0.16	0.09	-0.43	0.25	0.46	0.19	0.41
12	23	34	0.77	a	-0.28	a	0.82	0.48	0.67
13	37	22	0.66	a	-0.56	a	0.86	0.40	0.76
14	27	37	0.53	a	-0.33	a	0.62	0.22	0.58
15	12	61	0.71	a	-0.33	a	0.79	0.06	0.78
16	9	55	0.69	a	-0.37	a	0.78	0.09	0.77
17	20	80	0.69	a	-0.07	a	0.69	0.05	0.69
18	25	65	1.04	a	-0.32	a	1.08	0.15	1.07
19	39	65	0.84	a	0.00	a	0.84	0.35	0.76

$d$ -down, soil displacement downslope;  $d$ -across, soil displacement across the slope;  $d$ , total soil displacement;  $d_T$ , soil displacement in the tillage direction;  $d_P$ , soil displacement in the direction perpendicular to tillage.

<sup>a</sup> Since the position of the metal tracer cloud centre of mass is a single point, here the S.D. is substituted by the maximum average error of the calculated position, which is 0.1 m (Borselli and Torri, 2001).

when the soil is laterally overturned downslope (i.e.,  $S_P < 0$ ). These general tendencies are consistent with most of the translocation models in the literature and are shown in Table 6.

### 3.2. Calibrating the SETi model using data from field experiments

The SETi model was calibrated using the field data from Table 2 as inputs and applying an iterative

Table 3

Summary of statistical correlations between soil displacement and topography

	$d_T$	$d_P$	$S_{max}$	$S_T$	$S_P$
$d$	0.18	<u>0.92</u>	<u>0.39</u>	-0.13	-0.53
$d_T$		-0.22	0.45	<u>-0.70</u>	0.22
$d_P$			<u>0.20</u>	0.15	<u>-0.63</u>

$d$ , total soil displacement;  $d_T$ , soil displacement in the tillage direction;  $d_P$ , soil displacement in the direction perpendicular to tillage;  $S_{max}$ , maximum slope gradient;  $S_T$ , slope gradient in the direction of tillage;  $S_P$ , slope gradient in the direction perpendicular to tillage. Underlined correlations are significant at the  $P$ -value  $< 0.05$ .

method to minimize the average error of estimation for  $d$ -down,  $d$ -across and total displacement  $d$ . A specific optimisation code was implemented in the Matlab<sup>®</sup> environment, based on a differential evolution genetic algorithm (Storn and Price, 1997) and adopting all the additional setup strategies to ensure a global optimisation result, described by Storn and Price (1997) and Price (1999).

We used a modified version of the SETi equations describing the drag phase of motion (unpublished version). This modified version takes into account that the trajectory of the soil clouds along the mouldboard plough varies according to implement size and shape, and also depends on the depth and speed of tillage. Thus, distances of soil movement along the mouldboard, the actual trajectory along the bottom surface  $L_s$  (m) and projected distances in directions parallel to tillage  $L_x$  (m), lateral to tillage  $L_y$  (m), and in the vertical direction  $L_z$  (m), are calculated as functions of the depth of tillage  $D$  (m) and speed of tillage  $V$  ( $m\ s^{-1}$ ) using the equation:

$$L_{(x,y,z)} = VDL_{(x,y,z)} \quad (1)$$

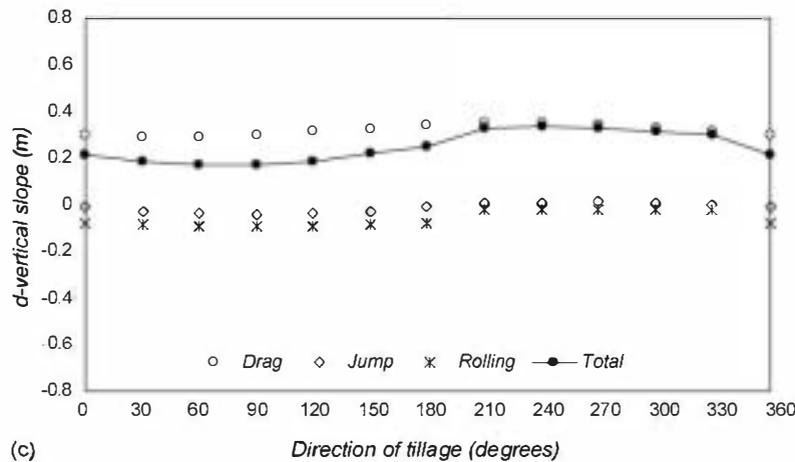
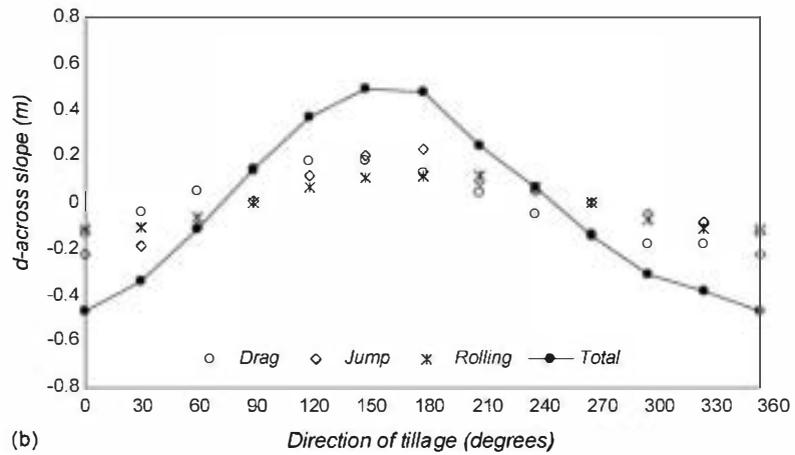
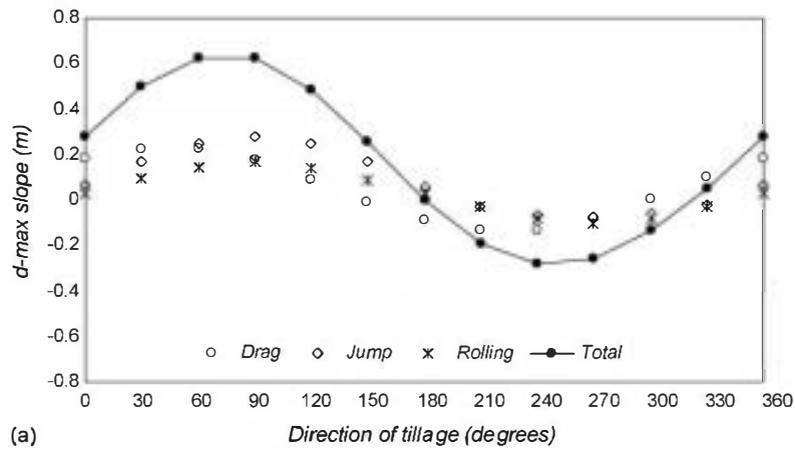


Fig. 5. Soil displacement simulated using the SETi model for the three phases of motion and total displacement along the directions of: (a) maximum slope; (b) across the slope; (c) vertical direction. (15% slope, 0.3 m tillage depth).

The coefficients  $L_{S(x,y,z,s)}$  in Eq. (1) usually range from 0.1 to 3.0, and are strictly dependent on the type of tool used to derive the experimental dataset. The relationships in Eq. (1) is characterised by the following conditions that must be satisfied to maintain a physical sense:

$$\lim_{D \rightarrow 0} L_{(x,y,z,s)} = 0 \quad (2)$$

$$\lim_{V \rightarrow 0} L_{(x,y,z,s)} = 0 \quad (3)$$

An additional constraint must be introduced in Eq. (1) due to the fact that soil movement is developed in 3D and the final movement components ( $x$ ,  $y$ ,  $z$ ) are linked to the total movement on the surface of the tool. So a simple additional constraint must be applied to the coefficients  $L_{S(x,y,z,s)}$ :

$$L_{S_s} > \sqrt{L_{S_x}^2 + L_{S_y}^2 + L_{S_z}^2} \quad (4)$$

The inequality (4) ensure that the following condition on the components of movement  $L_{S(x,y,z,s)}$ , computed with Eq. (1) is always satisfied:

$$L_S > \sqrt{L_x^2 + L_y^2 + L_z^2} \quad (5)$$

A summary of the parameters involved in calibrating the SETi model is provided in Table 4. Fig. 5 shows the displacement curve for the three phases of soil motion produced by a tillage operation conducted at a depth of 0.3 m on a 15% slope predicted by the SETi model after calibration using the field data shown in

Table 4  
Input and calibrated parameters for the SETi calibration

Input parameters	
Direction of overturning (right or left)	
Tillage speed (m s <sup>-1</sup> )	
Tillage depth, $D$ (m)	
Direction of tillage, $\omega$ (°)	
Steepest slope gradient, $S_{max}$ (%)	
Soil displacement downslope, $d$ -down (m)	
Soil displacement across slope, $d$ -across (m)	
Calibrated parameters	
Overturning angle direction, $\alpha$ (°)	97.4
Angle of soil ejection, $\phi$ (°)	58.4
Coefficients of the drag phase motion equations	
$L_{S_x}$	2.66
$L_{S_y}$	0.36
$L_{S_z}$	1.32
$L_{S_s}$	2.98

Table 2 and the calibration parameters in Table 4. To assess the performance of the SETi model using our experimental dataset (Table 2), predicted soil displacement versus observed displacement was plotted in Fig. 6. Corresponding to the reference system used by the SETi, the outputs are presented as the three separate plots: (a) displacement in the direction of steepest slope  $d$ -down; (b) displacement across the slope  $d$ -across and (c) total soil displacement  $d$ . The average estimation error shows a very narrow range from 11 cm (for the direction across the slope) to 12 cm (for the steepest slope direction and total displacement).

### 3.2.1. Assessment of the uncertainty associated with the optimized parameters using the SETi model

The assessment of uncertainty and sensitivity associated to the parameters optimized in a framework of any complex model is a relevant question in scientific and technical disciplines. The limitation of experimental dataset and the intrinsic complexity of the model adopted constraints to use advanced statistical and simulation techniques to obtain the desired information about the uncertainty and sensitivity of the parameters. In this study, we used the Bootstrap method to assess the robustness of the model SETi and the standard error, S.E. associated to each parameter calibrated. The Bootstrap method (Efron, 1979) is one of the effective statistical computer based method used to assess the uncertainty in statistics computed from finite samples (Duchesne and MacGregor, 2001). The method provides estimates of the S.E., which allow computing approximate confidence intervals with minimal number of assumption (Efron and Tibshirani, 1993).

The Vicarello site experimental dataset, characterised by the input parameters in Table 4, is a rectangular ( $m \times n$ ) matrix,  $x$ . The number of rows  $m$  represents the number of experiments conducted independently in the field site. Application of the Bootstrap method to the experimental dataset means to make a complete random resampling (row by row), with replacement of the original matrix  $x$  and produce a new subsample matrix  $x^*$ . This operation, called Bootstrap, is iterated  $B$  times. Each Bootstrap subsample  $x^*$  have the same size of the original dataset  $x$  and some rows may be replicate. The application of global optimization to each  $x^*$  will produce a population of optimal parameters and the goodness of fitting statistics, as the determination

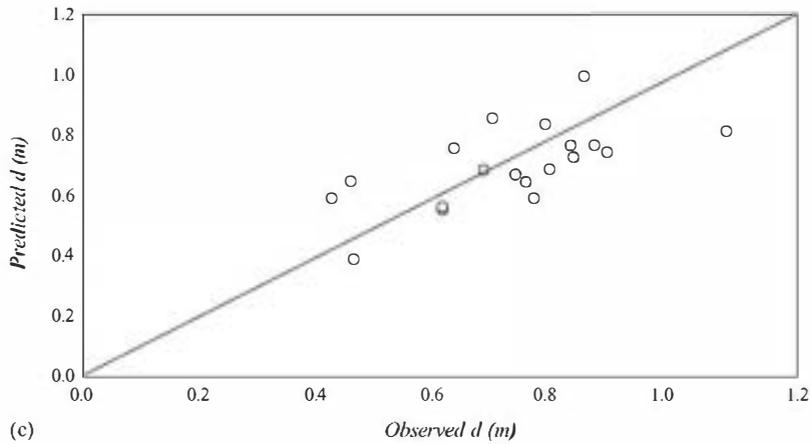
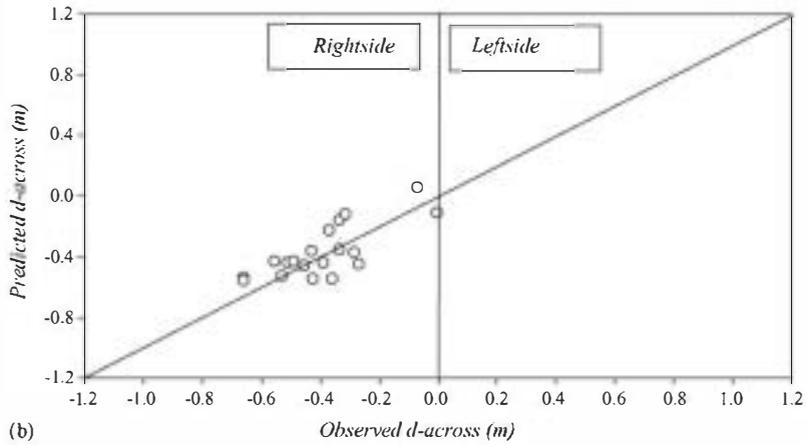
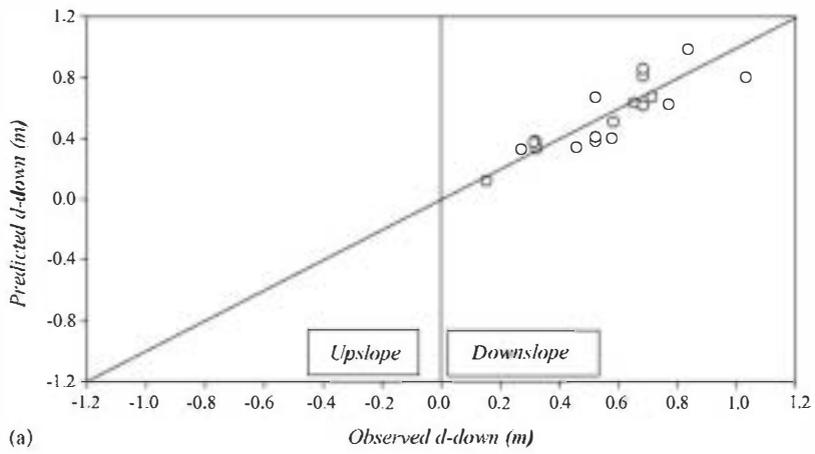


Fig. 6. Performance of the SETi model using the experimental dataset: (a) displacement in the direction of maximum slope  $d_{\text{down}}$ ; (b) displacement across the maximum slope  $d_{\text{across}}$ ; (c) total soil displacement  $d$ .

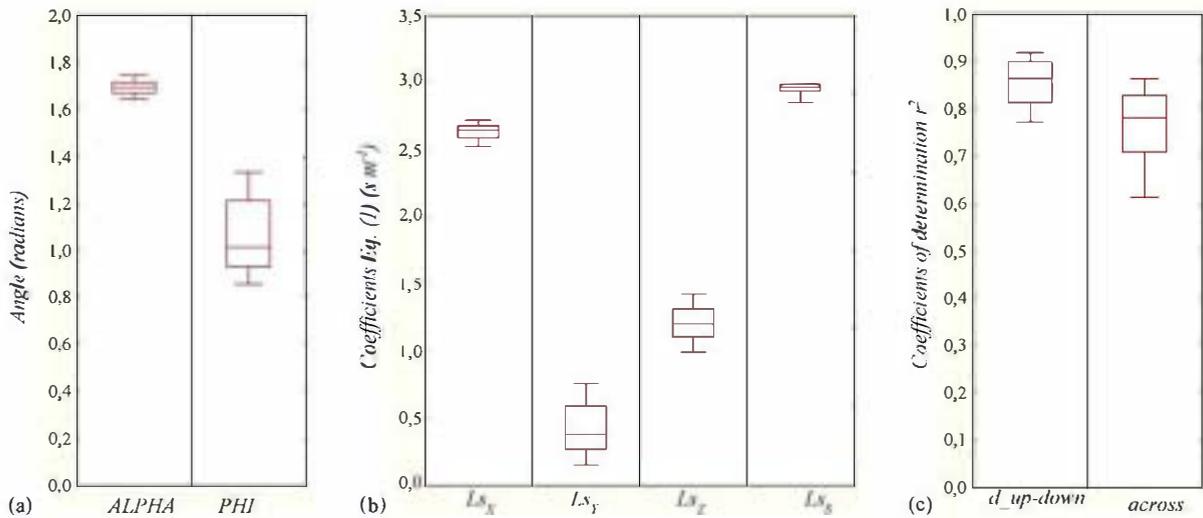


Fig. 7. Summary of the SETi calibration results applying the Bootstrap method to the Vicarello site experimental database (Table 2) and using a number of Bootstrap subsamples  $B = 100$ : (a) angles of overturning  $\alpha$  and soil ejection  $\phi$  (radians); (b) coefficients of the drag phase motion equation  $L_{S(x,y,z,s)}$ ; (c) distribution of the coefficient of determination  $r^2$  for the observed and predicted displacements in the X- and Y- directions. (Whiskers = 10 and 90%; box line = median.)

coefficient  $r^2$ . Following Efron (1982) the S.E. associated to a given parameter or statistics  $\theta$  is given by the following equation:

$$S.E. = \sqrt{\frac{\sum_{i=1}^B (\theta_i - \bar{\theta})^2}{B - 1}} \quad (6)$$

The number of Bootstrap subsamples is set by the user and is not limited to the number of observation in the original dataset. A large  $B$  allows one to gather more information about the S.E. in  $\theta$  and Bootstrap is more efficient with unsmooth model or non-linear statistics (Efron and Tibshirani, 1993). In this study, the Bootstrap method has been adopted with  $B = 100$ . This means that the global optimisation has been ran 100 times using  $B$  different Bootstrap subsamples of the same matrix  $x$  of experimental data. The Simulation was limited to  $B = 100$  due the huge computation time required for each optimization to be completed

satisfactorily. The results of the Bootstrap analysis are given in Fig. 7 and Table 5. In the Fig. 7, the whiskers represent, respectively, the 10 and 90% percentiles of the distribution for each parameter. The Table 5 shows the average value and S.E. for each parameter and the  $r^2$  values for the variables predicted,  $d_{up-down}$  and  $d_{across}$ . The results indicate the robustness of the model SETi and the limited uncertainty S.E. associated to each parameter calibration. The distribution of the  $r^2$  values, relative to the predicted and observed displacements in X- and Y-direction, indicate that the 90% of values fall in a more than acceptable range (Fig. 7c; Table 5).

### 3.3. Effect of tillage depth on soil displacement

To assess the effect of tillage depth on the intensity of soil translocation, SETi output relationships were

Table 5

Means and S.E. calculated for the SETi calibration parameters and  $r^2$  values for the predicted variables, applying the Bootstrap method ( $B = 100$  Bootstrap subsamples)

	Alpha (rad)	Phi (rad)	$L_{\alpha_x}$	$L_{\alpha_y}$	$L_{\alpha_z}$	$L_{\alpha_s}$	$r^2$ $d_{up-down}$	$r^2$ $d_{across}$
Mean	1.68	1.07	2.60	0.43	1.20	2.94	0.85	0.76
S.E.	0.12	0.20	0.23	0.24	0.18	0.09	-	-

used to develop synthetic regression models of the type:

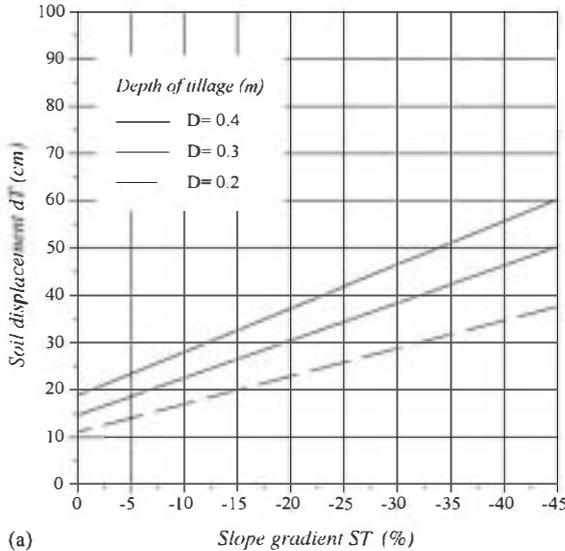
$$d = f\{S_T; S_P; D\} \quad (7)$$

which relates the soil displacement distance to the slope gradients  $S_T$  and  $S_P$  and depth of tillage  $D$ . Fig. 8a and b are plots of the distances  $d_T$  and  $d_P$  against the gradients  $S_T$  and  $S_P$ , respectively, for three depths of tillage, 0.2, 0.3 and 0.4 m. Each regression model was built using a total number of values of  $n = 108$ , corresponding to 9 values of maximum slope gradients ranging between 5 and 45% and 12 directions of tillage ( $\omega$  angles) between  $0^\circ$  and  $330^\circ$ . A summary of the regression results is showed in Table 6.

Regression analysis reveals that for both direction of soil movement, forward and lateral, displacement showed a strong direct relationship with the depth of tillage. In the case of soil movement parallel to the direction of tillage, for a tillage depth change from 0.2 to 0.4 m, the regression coefficient of the curves in Fig. 8a varies between  $-0.59$  and  $-0.92$ , and the regression constant shows a very narrow range, 11.1–18.8. The multivariate regression model is:

$$d_T = 3.36 - 0.76S_T + 38.54D \quad (8)$$

$(n = 324; r^2 = 0.94; p < 0.001)$



For the lateral displacement  $d_P$ , regression curves in Fig. 8b show significant higher values for the regression coefficients as well as for the interception. Regression coefficient varies between  $-0.84$  and  $-1.07$ , while the regression constant shows a narrow range, varying between 38.4 and 49.7. Multivariate regression analysis resulted in a high regression coefficient  $e = 56.6$  for the depth of tillage, which significantly differed from zero at a  $P < 0.001$ ; the multivariate model being:

$$d_P = 27.09 - 0.96S_P + 56.60D \quad (9)$$

$(n = 324; r^2 = 0.96; p < 0.001)$

For the total distance  $d$  along the actual trajectory of soil displacement, the multivariate regression model obtained is:

$$d = 27.51 - 0.22S_T - 0.86S_P + 73.05D \quad (10)$$

$(n = 324; r^2 = 0.92; p < 0.001)$

The strong direct relationship with  $D$  in Eq. (10) implies that the expected increase in total displacement  $d$  (cm) can be calculated for any increment of  $D$  (cm) using the linear relationship:

$$\Delta d = 0.73\Delta D \quad (11)$$

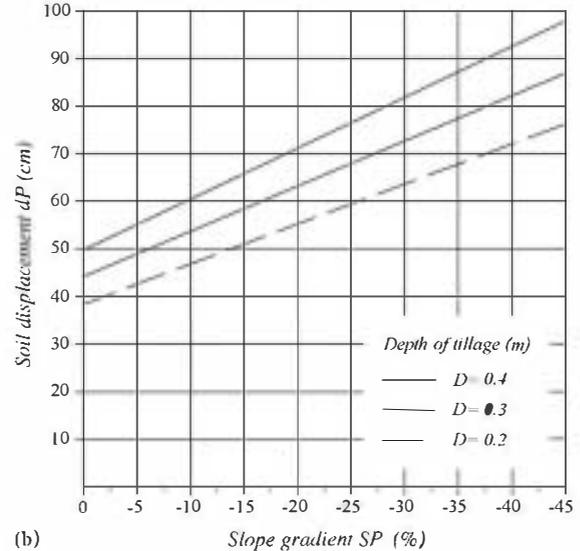


Fig. 8. Soil displacement in relation to the slope gradient using the SETi model predictions for three depths of tillage: 0.2, 0.3 and 0.4 m. (a)  $d_T$  vs.  $S_T$ ; (b)  $d_P$  vs.  $S_P$ .  $d_T$ , soil displacement in the tillage direction;  $d_P$ , soil displacement in the direction perpendicular to tillage;  $S_T$ , slope gradient in the direction of tillage;  $S_P$ , slope gradient in the direction perpendicular to tillage.

Table 6  
Comparing results with those of the literature

Reference	Depth of tillage, $D$ (m)		Slope gradient, $S$ (%)	Soil movement along the slope, regression analysis				Field methods
				$a$	$b$	$n$	$R^2$	
(a) Soil displacement in the direction of tillage, $d_T = a + bS_T$ (cm)								
Lindstrom et al. (1992)	0.24	Up- and downslope	From -9.4 to 9.4	34.2	-1.02	20	0.64	Excavation method
Revel et al. (1993)	0.27	Up- and downslope	-18 and 18	37.4	-0.75	2	-	Siliceous gravels
Govers et al. (1994)	0.28	Up- and downslope	From -22.7 to 22.3	28.0	-0.62	12	0.68	Excavation method
Lobb et al. (1995)	0.15	Up- and downslope	-5 and 5	29.4	-0.51	2	-	Labelled soil with $^{137}\text{Cs}$
Van Muysen et al. (1999)	0.33	Downslope	From -23 to -2	24.0	-1.39	6	0.89	Excavation method
	0.15	Downslope	From -25 to -5	12.0	-0.69	6	0.77	Excavation method
De Alba (2001)	0.24	Up- and downslope	From -30 to 25	38.3	-0.62	8	0.94	Excavation method
	$d_T = a + bS_T + cS_P$		$d_T = 38.03 - 0.62S_T + 0.40S_P$			11	0.88	
Geronidis et al. (2001)	0.20	Up- and downslope	From -9 to 22	16.0	-0.54	10	0.73	Excavation method
	0.30	Up- and downslope	From -9 to 22	30.0	-0.99	10	0.64	Excavation method
	0.40	Up- and downslope	From -9 to 22	38.0	-1.18	10	0.73	Excavation method
Van Muysen et al. (2002)	0.25 ( $V = 1.45 \text{ ms}^{-1}$ )	Downslope	From -23 to 0	39.0	-1.05	12	0.75	Excavation method
		Upslope	From 0 to 23	39.0	-			
	0.21 ( $V = 1.54 \text{ ms}^{-1}$ )	Downslope	From -23 to 0	30.0	-0.95	12	0.78	Excavation method
		Upslope	From 0 to 23	30.0				
0.21 ( $V = 1.81 \text{ ms}^{-1}$ )	Downslope	From -23 to 0	36.0	-1.39	12	0.77	Excavation method	
	Upslope	From 0 to 23	36.0					
This study								
Field experiments	From 0.27 to 0.42	Oblique direction	$S_T$ from -34 to -3	13.5	-1.06	19	0.48	Excavation and electromagnetic probe methods
SETi model <sup>a</sup>	0.20	From 0° to 360° <sup>ab</sup>	$S_T$ from -45 to -0	11.1	-0.59	108	0.90	Excavation and electromagnetic probe methods
	0.30	From 0° to 360° <sup>ab</sup>	$S_T$ from -45 to -0	14.7	-0.79	108	0.98	Excavation and electromagnetic probe methods
	0.40	From 0° to 360° <sup>ab</sup>	$S_T$ from -45 to -0	18.9	-0.92	108	0.99	Excavation and electromagnetic probe methods
$d_T = a + bS_T + cS_P + eD$	0.20, 0.30, 0.40	From 0° to 360° <sup>ab</sup>	$S_T$ and $S_P$ from -45 to -0			324	0.94	
		$d_T = 3.4 - 0.76S_T + 38.5D$						

Table 6 (Continued)

Reference	Depth of tillage, $D$ (m)	Slope gradient, $S$ (%)	Soil movement along the slope, regression analysis				Field methods	
			$a$	$b$	$n$	$R^2$		
(b) Soil displacement in the direction perpendicular to tillage, $d_p = a + bS_p$ (cm)								
Lindstrom et al. (1992)	0.24	Contour	From -14.0 to 12.8	44.3	-1.12	20	0.81	Excavation method
De Alba (2001)	0.24	Contour	From -20 to 20	41.4	-0.50	5	0.94	Excavation method
Geronidis et al. (2001)	0.20	Contour	From -22 to 22	24.0	-0.58	6	0.76	Excavation method
	0.30	Contour	From -21 to 17	31.0	-0.73	6	0.75	Excavation method
	0.40	Contour	From -23 to 21	37.0	-0.78	6	0.89	Excavation method
Van Muysen et al. (2002)	0.26	Contour	From -23 to 23	48.0	-0.38	12	0.73	Excavation method
This study								
Field experiments	From 0.27 to 0.42	Oblique direction	$S_p$ from -35 to 2	52.7	-1.17	19	0.40	Excavation and electromagnetic probe methods
SETi model <sup>a</sup>	0.20	From 0° to 360° <sup>b</sup>	$S_p$ from -45 to -0	38.4	-0.84	108	0.91	Excavation and electromagnetic probe methods
	0.30	From 0° to 360° <sup>b</sup>	$S_p$ from -45 to -0	44.1	-0.95	108	0.96	Excavation and electromagnetic probe methods
	0.40	From 0° to 360° <sup>b</sup>	$S_p$ from -45 to -0	49.7	-1.07	108	0.97	Excavation and electromagnetic probe methods
$d_p = a + bS_T + cS_p + eD$	0.20, 0.30, 0.40	From 0° to 360° <sup>b</sup>	$S_T$ and $S_p$ from -45 to -0 $d_p = 27.1 - 0.96S_p + 56.6D$			324	0.96	
(c) Total soil displacement, $d = a + bS_T + cS_p + eD$ (cm)								
This study	0.20, 0.30, 0.40	From 0° to 360° <sup>b</sup>	$S_T$ and $S_p$ from -45 to -0 $d = 27.5 - 0.22S_T - 0.86S_p + 73.05D$			324	0.96	

<sup>a</sup> Synthetic soil translocation models derived from the calibrated SETi model.

<sup>b</sup> Direction of tillage  $\omega$  (°) defined as the counter-clockwise angle between the trajectory of the tractor and the slope aspect. For the regression analysis, 12 tillage directions between 0° and 330° at intervals of 30° were considered.

Although, every the regression coefficient in Eq. (10) is significantly different from zero ( $P < 0.001$ ), when all the independent variables are standardised, the highest relative contribution of  $S_P$  to the total displacement  $d$  becomes more evident. The standardised regression coefficients ( $\beta$  coefficients) are  $-0.88$  for the slope  $S_P$ ,  $0.31$  for tillage depth  $D$  and  $-0.22$  for the slope  $S_T$ . Hence the relative contribution of the slope  $S_P$  is near three times the contribution of depth of tillage and four times that of the slope  $S_T$ . The predominance of the effect of the slope gradient over the depth of tillage is still present in the two components of soil movement. In the case of forward displacement  $d_T$ , in Eq. (8),  $\beta$  coefficients are  $-0.95$  for the slope  $S_T$  against  $0.20$  for  $D$ ; while, for lateral displacement  $d_P$  in Eq. (9),  $\beta$  coefficients are  $-0.95$  for the slope  $S_P$  and  $0.23$  for  $D$ .

This general trend of soil displacement increasing with tillage depth is in agreement with previous experimental results for mouldboard ploughing reported by Lobb et al. (1999), Gerontidis et al. (2001) and Van Muysen et al. (2002). Nonetheless, Van Muysen et al. (2002) found that longitudinal translocation distances ( $d_T$ ) were strongly affected by tillage depth, while lateral displacement distances ( $d_P$ ) were not significantly related. These authors suggested that the depth of tillage only affects the time during which the soil stays in contact with the mouldboard blade before being ejected (i.e., the drag phase of soil motion) and consequently the distance soil is displaced in a parallel direction to the tractor path. Nevertheless, this lateral soil displacement is always approximately equal to the furrow width and is accordingly unrelated to the duration of the drag phase or tillage depth. The SETi model predicts that tillage depth also affects the equations that describe the “jump” and “rolling” soil motion phases. Indeed, tillage depth alters the path followed by soil clods on the implement surface and consequently the overturning angle direction (angle  $\alpha$ ), angle of soil ejection (angle  $\phi$ ), and velocity at which the clods are ejected from the instrument (Torri and Borselli, 2002). Moreover, the nature of the tillage depth effect will depend on the shape and size of the implement. Hence, results suggest that the different effects of tillage depth observed in previous studies could reflect differences in the shape of the mouldboards used.

To evaluate the fit of the multivariate model in Eq. (10) to the dataset derived from the field

experiments at the Vicarello site, a value of 13.8 cm was obtained for the average error of estimation. This error is acceptable considering that the maximum error calculated for the instrument set-up used in field experiments was around 10 cm (Borselli and Torri, 2001). In contrast, no regression models with predictive capacity were obtained when a similar multivariate analysis was performed by directly using the dataset for soil translocation collected in the field experiments (Fig. 4). This reflects the considerable improvement related to the use of the physically based SETi model to analyse data derived from field experiments. The SETi model can be calibrated with a relatively small experimental dataset to yield more general and synthetic soil translocation models of the type  $d = f\{S_T, S_P, D\}$ . One of the main advantages of these synthetic models is that they can be used to extrapolate results to a much wider array of scenarios than those in which the experiments are performed, in terms of topography complexity and directions and depth of tillage. A further advantage of the use of synthetic relationships is that they can be directly applied to calibrate other models of soil redistribution for a given tillage implement on the field- or landscape scale. The latter is the subject of a follow-up paper, in which soil translocation equations obtained using the SETi model are used to calibrate the Soil Redistribution by Tillage (SORET) model (De Alba, 2003), and to perform 3D simulations of soil redistribution by tillage for several agricultural landscapes and tillage scenarios.

Further experimental work is needed to quantify the effect of tillage velocity,  $V$ , on soil displacement and therefore more accurately calibrate the SETi model. Indeed, the factor tillage speed  $V$  could be included in synthetic multivariate models to produce algorithms of the type:

$$d = f\{S_T, S_P, D, V\} \quad (12)$$

Additional research would also be needed to characterise the effect of the initial soil conditions on tillage translocation as well as on soil-implement interactions.

### 3.4. Implications of asymmetric soil movement provoked by mouldboard ploughing

As discussed before, soil movement by the mouldboard plough is non-symmetric. The soil is

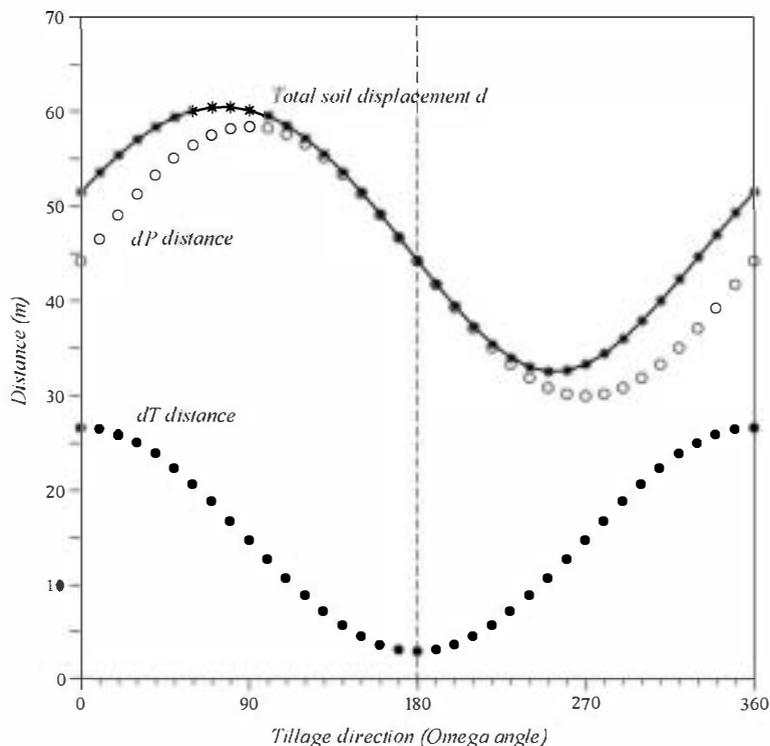


Fig. 9. Predicted distances of soil displacement in the directions: total soil trajectory,  $d_T$  direction, and  $d_P$  direction; for a single tillage operation conducted at a 0.3 m depth on a 15% slope along directions of tillage  $w$  between  $0^\circ$  and  $360^\circ$  ( $0^\circ$  = downslope tillage;  $180^\circ$  = upslope tillage).  $d_T$ , soil displacement in the tillage direction;  $d_P$ , soil displacement in the direction perpendicular to tillage.

pushed forward in the direction of the tractor motion but also towards a lateral direction, producing a trajectory of soil movement along an oblique direction in relation to that of tillage.

Fig. 9 shows the predicted distances  $d$ ,  $d_T$  and  $d_P$  for simulation of a single tillage operation on a 15% slope along directions of tillage ranging from  $0^\circ$  to  $360^\circ$  ( $\omega$ ). The results reflect the significance of the asymmetric nature of the soil movement produced by mouldboard ploughing and the predominant effect of lateral displacement  $d_P$  on the actual soil motion trajectory.

The maximum absolute distance  $d$  was obtained for a tillage direction of ca.  $80^\circ$  and the minimum  $d$  was provoked by a direction of ca.  $250^\circ$ , with values of 60.5 and 32.5 cm, respectively. Of the two components of displacement  $d_P$  and  $d_T$ , the former was always significantly higher, i.e.,  $d_P$  showed values 1.5–15.5 times higher than the distance  $d_T$ . The  $d_P$  distance was in the range 54.8–27.9 cm, corresponding to directions of tillage of  $90^\circ$  and  $270^\circ$ , respectively;

while  $d_T$  was in the range 26.5–2.8 cm for tillage directions of  $0^\circ$  and  $180^\circ$ , respectively.

When these results were compared to those previously reported by De Alba (2001) for tillage translocation by a typical mouldboard used in Central Spain (Fig. 10), similar relationships were observed among  $d$ ,  $d_T$  and  $d_P$ . However, the prevailing effects of the partial distance  $d_P$  on absolute soil displacement were not as strong. The relation  $d_P/d_T$  varied between extreme values of 0.7 and 1.7. As a consequence, maximum displacement  $d$  corresponded to downslope tillage (i.e., direction of  $0^\circ$ ) and its minimum value to a tillage direction ca. the upslope direction (i.e., direction of  $200^\circ$ ), with  $d$  values of 62.9 and 49.9 cm, respectively. These differences between the results of simulation are probably related to the different shape and size of the mouldboard ploughs used in the experiments of Vicarello and Central Spain.

It is important to stress the lack of studies in which the asymmetric nature of soil movement is taken into

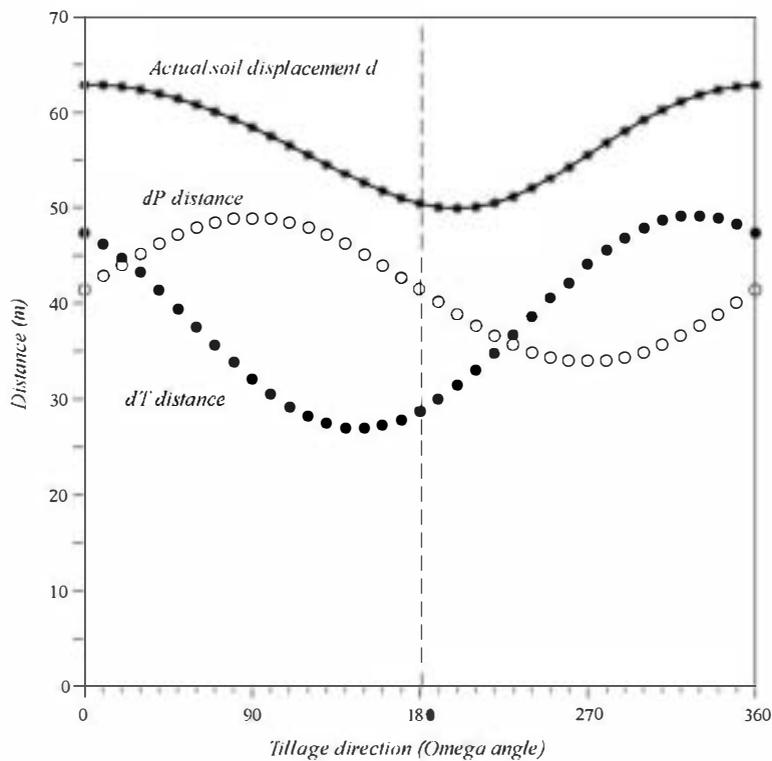


Fig. 10. Predicted distances of soil displacement for a single tillage operation conducted at a 0.24 m depth on a 15% slope using a mouldboard plough typical of Central Spain (modified from De Alba, 2001).  $d_T$ , soil displacement in the tillage direction;  $d_P$ , soil displacement in the direction perpendicular to tillage.

account to model soil translocation by mouldboard ploughing. This in part can be explained by the fact that tillage translocation has been defined as a so-called diffusion-type process (Govers et al., 1994) described by a single constant  $k$  (i.e., the diffusion constant or the so-called tillage transport coefficient). This approach makes an important simplification by assuming that soil transport by tillage is only affected by the slope gradient in the direction of soil movement considered (e.g., Van Muysen et al., 2002). The results presented here together with those reported in De Alba (2001) and Torri and Borselli (2002) stress the inadequacy of this assumption. A single  $k$ -factor, the coefficient of tillage transport, cannot properly quantify the soil translocation caused by mouldboard ploughing, which requires the use of more complex models that take into account the complexity of interactions between the topography and tillage patterns in a more realistic manner. The method used here represents a notable improvement over past

models in that topography complexity is dealt with in two different ways: (1) by combining the directions of the steepest slope and tillage ( $\omega$ ) in the reference system implemented in the SETi model and (2) by combining the orthogonal slope gradients  $S_T$  and  $S_P$ .

To analyse the predicted spatial pattern of soil translocation using the translocation models in Eqs. (8–10), the displacement trajectory of an idealized soil block was simulated (single tillage operation conducted on a 15% slope in tillage directions, i.e.,  $\omega$  between  $0^\circ$  and  $360^\circ$ ) to give the results shown in Fig. 11. These results show that the maximum value of soil translocation downslope (60.5 cm) corresponded to a tillage operation conducted in a direction of ca.  $70^\circ$ , while maximum soil translocation upslope (32.5 cm) was produced by conducting tillage in a ca.  $250^\circ$  direction. It should be highlighted that tillage along the steepest slope (i.e., tillage direction of  $0^\circ$ ) gave rise to a soil displacement distance downslope of 26.5 cm, i.e., 44% of the

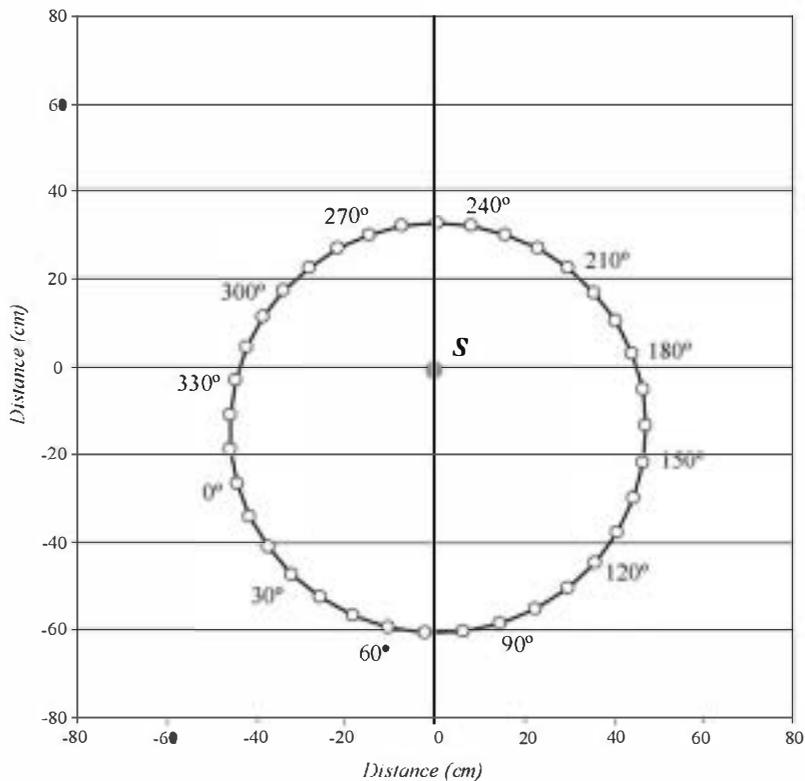


Fig. 11. Predicted final position (white circles) of a soil block S after a single tillage operation performed at a 0.3 m depth using a right-hand mouldboard plough on a 15% slope along directions of tillage ( $\omega$ ) between 0° and 360°.

maximum displacement obtained for the 70° direction. In contrast, tillage conducted upslope (i.e., a tillage direction of 180°) led to a soil displacement upslope of 2.8 cm, which only represents 8.7% of the maximum displacement obtained for a direction of 250°. For tillage performed across the slope (i.e., contour tillage), a downslope soil displacement of 58.4 cm was observed when the soil was overturned laterally and downwards (i.e., a tillage direction of 90°), while soil displacement upslope was 29.9 cm when the soil was overturned laterally and upslope (i.e., tillage direction of 270°). These results indicate that soil displacement along the steepest slope is zero for tillage directions of ca. 175° and 330°, while displacement across the slope is zero for tillage directions ca. 70° and 250°.

Thus, simulated results reveal that downslope tillage does not necessarily lead to maximum downslope soil transport. Moreover, contouring tillage with lateral overturning in a downward direction (i.e., a 90°

direction) causes a soil displacement downslope 2.2 times higher than downslope tillage along the steepest slope. Even in the case of alternating the tillage direction in consecutive operations up- and downslope (180° and 0° directions) and contouring (90° and 270° directions) after two such tillage operations, net soil displacement downslope is significantly higher for contour tillage; results being 28.5 cm versus 23.7 cm for upslope-downslope tillage and therefore 17% lower than the former. These trends are obviously related to the particular characteristics of the mouldboard plough used in the field experiments, and mainly to the observed predominant effect of the lateral displacement  $d_p$  on the actual trajectory of soil movement.

The experimental results reported by Lindstrom et al. (1992) indicate a similar trend: soil displacement downslope was higher for contour tillage (alternating the direction of tillage) than for upslope-downslope tillage. If we apply the translocation models reported

by these authors (Table 6) to simulating tillage on a 15% slope, predicted net soil displacement downslope is 33.6 cm for contour tillage versus 30.6 cm for tillage along the steepest slope. Additional support for net soil translocation downslope being higher for contour tillage than for upslope-downslope tillage can be found in De Alba (2001). In contrast, Gerontidis et al. (2001) and Van Muysen et al. (2002) concluded that contour tillage is less erosive than upslope-downslope tillage. However, the relationship between soil displacement and the slope gradient reported by Gerontidis et al. (2001) was weak, and thus of low predictive capacity for use in simulations. Similarly, the results of Van Muysen et al. (2002) are strongly conditioned by the fact that no significant relationship was found between slope gradient and soil displacement for upslope tillage (Table 6). This could be related to the particular experimental conditions and the type of mouldboard plough used in the field experiments.

#### 4. Conclusions

Our findings demonstrate that spatial patterns of soil redistribution due to mouldboard ploughing are highly variable and dependent on the particular characteristics of the mouldboard used. This dependence is so strong that maximum downslope soil translocation can take place both during contour tillage or up-down tillage. For the particular mouldboard used here, results indicate that maximum downslope soil transport occurs at a tillage direction of ca. 70°.

The lateral slope gradient  $S_P$  and tillage depth  $D$  were found to be the dominant controlling factors for total soil displacement. The effect of the slope gradient in a direction parallel to tillage  $S_T$  was much less pronounced. These findings highlight the importance of the asymmetric nature of the soil movement produced by mouldboard ploughing and the predominant effect of the lateral displacement  $d_P$  on the actual trajectory of soil motion.

It was clearly shown that there are complex interactions between the topography, direction of tillage and depth of tillage. Thus, even in the simplest case of alternating up- and downslope tillage, the process of soil translocation during mouldboard ploughing cannot be described as a diffusion-type

process governed by a single diffusion coefficient  $k$  (i.e., the so-called coefficient of soil transport). The adequate modelling of soil translocation due to mouldboard ploughing requires the use of multivariate models that take into account the forward and lateral components of soil movement,  $d_T$  and  $d_P$ , respectively, as well as the effect of the slope gradient in both orthogonal directions  $S_T$  and  $S_P$ .

The findings of this study reflect the potential of the combined approach applied. The physically based SETi model can be properly calibrated with a relatively limited dataset derived from field experiments. Once calibrated, the SETi model can be used to generate synthetic tillage translocation relationships that predict the intensity and spatial pattern of soil translocation across a much wider range of tillage scenarios than the particular experimental conditions, in terms of topography complexity (slope gradients and morphology) and the direction and depth of tillage. Finally, these synthetic relationships are useful tools for designing strategies aimed at minimising tillage erosion.

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