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The Techniques of Reducing Adhesion and Scouring Soil by Bionic – Review of Literature

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Abstract: Soil adhesion is a complicated multiple phase system influenced by many factors such as soil type, soil moisture content, contact material characteristics, working speed and external forces and environment. Adhesion of soil on the surfaces of soil-engaging components of various machines and equipment affects the quality of the work and in extreme cases; it does not allow the machine to move in moist sticky soil conditions. Moreover, adhesion of soil on the surfaces of ground engaging components of various machines and equipment increases the draft and energy consumption of these machines. Different techniques are employed to reduce adhesion of soil to the surfaces of these machines and equipment. This paper reviews some of the common techniques employed in reducing adhesion and scouring soil from the surface of agricultural machinery and equipment. It reviews the advantages and disadvantages of using these techniques and their limitations in practical field conditions. An ideal technique should be safe and simple, economical to manufacture, easy to use, synchronise with other components of the machine and tools, no requirement for extra controls and power, less energy consuming and efficient with scouring abilities 90% or higher. Some techniques such as air injection is useful but it adds on weight to the existing set up and in many cases makes the system more complicated to operate. Enamel coating is cheap and comparatively simple technique for reducing adhesion. It has poor wear resistance and cannot be used in abrasive soil conditions. The soil adhesion preventing mechanism of soil animal's cuticles addresses some of these issues. The surface characteristics of soil animal's cuticles have excellent scouring abilities and may be applied on the surfaces of soil engaging components of tillage tools. Ultra High Molecular Weight-Polyethylene (UHMW-PE) has better scouring characteristics and wear resistance. This could be applied for bionic modification of the surfaces of these tools for reducing adhesion and improving performance of a number of machines and equipment in sticky soil conditions.
Key Words: adhesion; bionic; soil; osmotic; vibration; lubrication

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1. INTRODUCTION

Soil adheres to the surfaces of soil engaging components of various machines and equipment. It not only affects the performance of machines and quality of work but also increases energy consumption. Enamel coated tines saved power by up to 22% when operating at 1.5 km/h speed during the first pass as compared to uncoated tines operating under similar conditions (Salokhe et al., 1999). It increase working resistance of ploughs (Qaisrani et al., 1992) and significantly affects the working ability of soil engaging components of agricultural machinery (ZHANG and HAN, 1992). The phenomenon of soil 'stickiness' has always occupied a prominent place among soil scientists, engineers and farmers as it is one of the soil's most troublesome physical properties. An excessively sticky soil makes cultivation difficult and prevents the harvesting of root crops in a clean condition. In extreme cases it does not allow the machine to move and work (Qaisrani, 1987).

Moreover, the vehicles that take soil as an actuating medium, or farm implements, earthmoving machines and hand tools that take the soil as a working object, all suffer from soil adhesion. It affects the efficiency and working quality of the machines adversely, and increases energy consumption. Qian and Zhang (1984) estimated up to 50% of the gross energy consumed by tillage operation is to overcome the adhesion and friction between soil and tillage tools. Qaisrani et al. (1992) and Qaisrani (1993) strongly supported these results.

Soil adhesion can be reduced by techniques such as lubrication (TONG et al. 1999), electro-osmosis (CONG et al., 1995; REN et al., 1995), mechanical vibration (WANG et al., 1998), and ultrasonic vibration (Sharma et al., 1977). Tong *et al*. (1990) also found that phosphorus has the ability of reducing adhesion between two surfaces. Zhang *et al*. (1986) suggested reducing adhesion by hydrophobic treatment of steel components. Salokhe and Gee-Clough (1987, 1988) used another approach for reducing adhesion by coating lug surfaces with different materials including silicon lubricant oil, lead oxide paint, gloss paint and varnish, chromium painting, teflon tape, teflon sheet, ceramic tile and enamel coating. They reported that lug coating can reduce soil adhesion to its surface considerably. However, there were practical problems (expensive and low durability, etc.) in using silicon lubricant oil, teflon tape, ceramic tile and enamel coating.

Experience showed that soil animals possess significant capability of reducing soil adhesion to their bodies. Surface morphology and special chemical constitutions of their body surfaces play important role in scouring soil. Ren *et al*. (2001) reported that soil animals prevented adhesion of soil to their bodies because of the evolution of their biological systems. Chen *et al*. (1990) found that soil animals prevent adhesion of soil to their bodies because of their outer shape and structure, presence of anti-adhesive elements and biological electrical system in their body surfaces, and secretion of some special elements. Zu *et al*. (2006) and Yan *et al*. (2007) demonstrated that earthworms reduce adhesion of soil to their bodies because of electro-osmotic flow of lubricating fluid at the body and soil interface. Gao *et al*. (2010) supported these results. This study reviews the practical application of some of these techniques and the soil adhesion preventing mechanism of soil animals on the surfaces of soil engaging components of various tools.

2. REVIEW OF LITERATURE

Soil adhesion, one of the important properties of soil, in its simplest form could be defined as sticking of soil to the surfaces of other materials. Adhesion of soil to the ground engaging components of tillage tools vary from soil to soil. The normal force of adhesion can mathematically be expressed as follows:

$$P = F/A \qquad (1)$$

P = normal component of adhesive force, N/cm^2
F = force acting perpendicular to the projected area of contact surface, N
A = projected area of tool in contact with soil, cm^2

When tillage tools are moving, there is some sliding resistance between soil and the tool surface. This sliding resistance is referred as tangential component of adhesive force. This may mathematically be expressed in its simplest as follows:

$\tau = C + N \tan\alpha$ (2)
τ = tangential component of the adhesive force, N
C = coefficient of adhesion, N/cm^2
N = normal pressure, N/cm^2
α = soil metal friction angle, degrees

When normal pressure equals to zero, then $\tau = C$. Most of the tillage tools working in the soil come under this category. Measurement of adhesive force is a key element in determining the tool performance in different soils. Fountain (1954) measured the normal component of soil adhesive force in the laboratory by using a circular metal plate as a working object. Finally, he developed an instrument used to measure soil adhesive forces. Later on many other scientists continued the work and developed more precise instruments for measuring soil adhesive forces (both normal and tangential components). Chinese scientists developed a simple hydraulic electro type instrument for measuring adhesive force. Jilin University developed another system of measuring the adhesive forces. It is the combination of electronics, mechanical and pneumatic techniques. The system is very simple to use, easy to operate, cheap and reliable. It has the capability of measuring the adhesive forces even greater than the cohesive forces of soils. Where as majority of the instruments measure the adhesive forces of soil accurately when these forces are less than cohesive forces of soil.

2.1 Mechanism of soil adhesion

Mechanism of soil adhesion has been investigated by various scientists and researchers from different angles and perspective. Based on the research outcome, various theories are presented. Fountain (1954) and some other scientists presented the theory of capillary. Fisher and Baver (1928) considered either the normal or tangential force is produced by the formation of water film of constrained water. Hua (1965) produced five boundary layers for the adhesion of soil. Zhang (1985) proposed that the soil adhesive force is the algebraic sum of the six forces.

$P = p_m + p_e + p_c + p_v + p_w + p_g$
P = soil adhesive force
p_m = sum of the molecular forces of soil molecules contact with other bodies.
p_e = sum of the forces of electro-static attraction between contact surfaces.
p_c = sum of the capillary forces produced by surface of meniscus formed by soil liquid with contact surface.
p_v = viscous resistance of soil liquid.
p_w = wedged pressure produced by potential chemical non equilibrium between liquid film of area of contact and void liquid.
p_g = negative air pressure produced by closing of soil pores of the area of contact of soil and other surfaces.

Nichols (1931) describes that the area of contact has significant role on various components of soil adhesive force. Capillary forces are one of the major components of soil adhesive force followed by magnetic properties of soil.

2.2 Law of soil adhesion

Soil adhesion is a complicated multiple phase process influenced by many factors. To formulate the law of soil adhesion, scientists have conducted a series of experiments leading to the following facts:

a) **Soil type:** Clayey soils are more adhesive than loamy and sandy soils. In other words, the adhesive force is inversely proportional to the diameter of soil particles. Nichols (1931) reported that adhesive force is directly proportional to the gum body contents of the soil. Moreover, adhesive forces of clay soils vary from soil to soil depending on the type of clay particles, their size and parent material, etc. These forces also depend on the cation exchange capacity of soil. Chen *et al.* (1993) reported that the adhesive force of soil decreases according to the order: K^+, Mg^{++}, Ca^{++}, H^+, Fe^{+++}, Al^{+++}. The presence or absence of organic matter and its contents in soil has significant effect on adhesive forces. For example, acidic soils are less adhesive than the soil containing fresh rotten materials. Adhesive force increases with the increase in soil moisture contents; reaches its maximum value and decreases with any further increase in moisture contents as shown in Fig. 1. Generally, adhesive force is maximum when the moisture contents are between plastic and liquid limits. Zhang (1985) investigated the effects of soil bulk density and moisture contents on their adhesive properties. Loose dry soils are less adhesive than the moist dense soils. The results of this study showed that the disturbed soils are 2 to 3 times less adhesive than undisturbed soils.

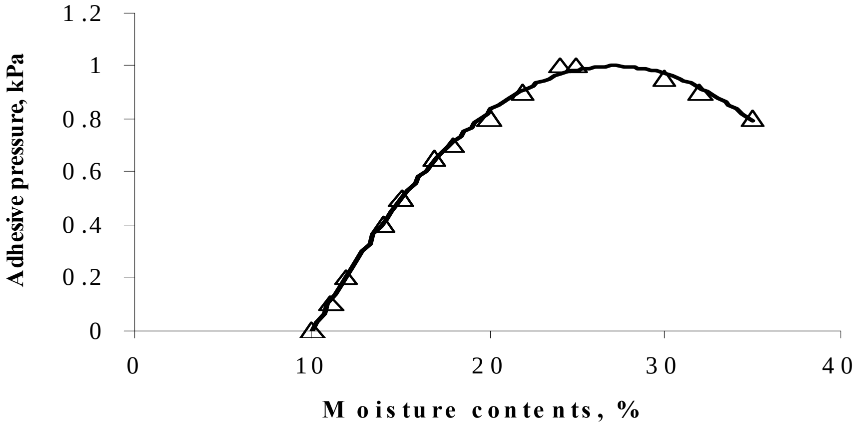

Figure 1: Relationship between moisture contents and adhesive pressure

b) **Material in contact with soil:** Zhang (1985) reported that adhesive forces vary from material to material. It increases with the increase in the free surface energy of the contact surfaces. The geometry of contact surfaces also influences the forces of adhesion. Qaisrani (1993) and Tong (1992) found that spherical convexes made from Ultra High Molecular Weight - Poly Ethylene (UHMW-PE) reduced the adhesive forces and improved the scouring properties of bionic bulldozing plates and mouldboard ploughs.

c) **External forces and environment:** Zhang (1985) found that adhesive force increases linearly with the normal pressure as shown in Fig. 2. This increase is linear until normal force achieves a value of 30 kN. The adhesive force then increases sharply with any further increase in the normal force.

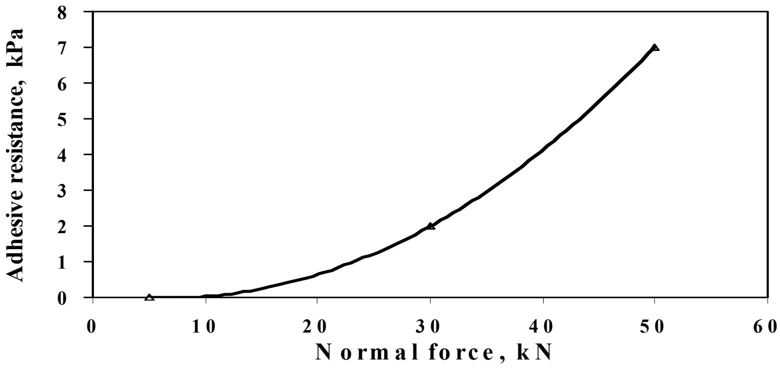

Figure 2: Relationship between normal force and adhesive resistance

2.3 Some of the techniques used to reducing reduce soil adhesion

Soil scouring could be improved by a number of ways. Some of the common techniques used in scouring soil from the surfaces of various tool include liquid injection, pneumatic, combination of the pneumatic and liquid injection, vibration, mechanical, heating, electro osmosis, modifying shapes and geometries of the tool surfaces, coating, and bionics, etc.

2.3.1 Air and liquid injection to scour soil

Air or other liquid are injected at soil-tool interface to improve soil scouring. The liquid acts as a lubricant and prevents adhesion of soil by aiding free flow of soil over the surface. The formation of air cushion or liquid film at soil-tool interface is helpful in reducing the contact of soil with the tools. The air and liquid injection at soil-tool interface improves the performance of the tools and requires some additional components for the application of fluid. This technique has been useful in minimizing the adhesion from the surfaces of excavators, earthmoving machinery, ploughs, etc. However, the quantity of water required as lubricant makes the technique impractical in a number of situations. For example, more than 16 litres/ha water is required to achieve a desired level of scouring from the plough surfaces. Moreover, it is better to use air as lubricant for soils which absorb large quantities of water (CHEN et al. 1990).

2.3.2 Heat to reduce adhesion and score soil from the tools

The application of heat in reducing adhesion of soil to the surface of tools has been explored in a number of experiments. The heat energy requirements for achieving a desired scouring rate were not studied thoroughly in these experiments and no practical methods have been developed. Nichols (1931) produced some quantitative data on heat and soil adhesion. The coefficient of hot slider was considerably less than the wet slider. No information is available on the temperature values used and the quantity of heat and heat losses from the slider. These experiments were conducted on dry sand with negligible adhesion. However, it may provided some useful information on the effects of heat on friction as shown in Table 1. The efficacy of this technique cannot be verified as it has never been tried in practical field conditions.

Although this technique reduces soil adhesion by minimising surface tension of water film at soil-tool interface but adhesion may increase if suboptimum level of heat is applied. The exhaust air could be used as a source of heat in practical field conditions. This technique may be useful when excavating frozen soils. However, this technology is complicated because of its construction and may not be safe to use for the operators.

2.3.3 Electro-osmosis to reduce adhesion

The increase in the thickness of water film at the soil-tool interface reduces the adhesive forces significantly. Soil electro-osmosis can be used to increase the thickness of water film. There is an electrochemical double layer on the surface of clay particles and metallic tools are good conductors of electricity. Soil adhesion can be reduced by forcing out some of the soil water to act as lubricant at the soil-tool interface by electro-osmosis. The electro-osmosis time is shorter because of the continuous operation of tools. Therefore, its potential applications in field conditions may be very limited. Moreover, when the tools are operating at higher speeds, the time for electric current to pass through the soil is further shortened. This will reduce the thickness of water film acting as lubricant at the soil-tool interface. Therefore, the application of this technique in practical field conditions is limited. Mackson (1962) investigated electro-osmosis by using a range of voltages (50-100V) at a range of speeds from 1.25 m/s to 150 m/s. The draft of steel slider was expressed mathematically with the inclusion of all the factors as follows:

$$F = 0.636 + 9.88\times10^{-4}V - 1.59\times10^{-3}E - 9.22\times10^{-3}W + 0.514P^2$$

F = draft, N
V = speed, m/s
E = potential, volts
W = soil moisture contents, %

P = normal force, N

This technique can be used for reducing adhesion and scouring soil in excavators. The time of static touch between soil and shovel is approximately 13 seconds and electro-osmosis may be applied effectively in this time interval. This technique was successfully evaluated in the laboratory. The assessment of adhesive forces for electro-osmosis and non-electro-osmosis techniques at a range of soil moisture contents (CHEN *et al*. 1990) is presented in Fig. 3.

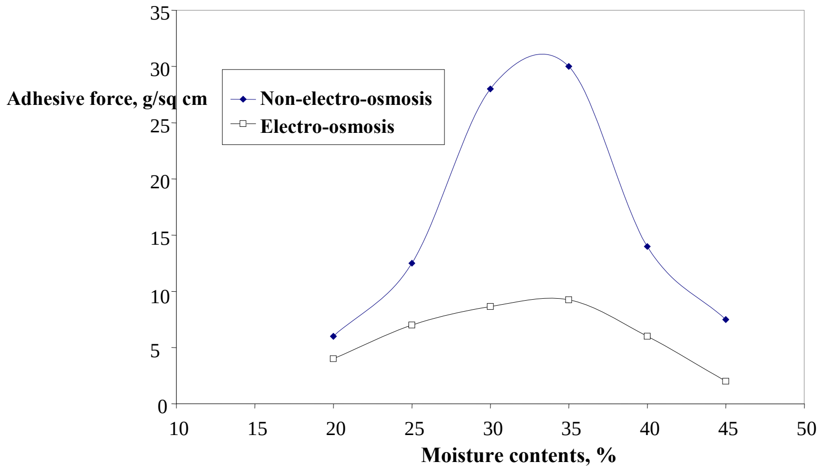

Figure 3: Relationship between adhesive force and soil moisture content (derived from Chen *et al.* 1990).

Fig. 4 shows the relationship of adhesive force and the time of electro-osmosis. The longer the electro-osmosis time, the more water moves out and creates a thick water film at soil-tool interface. This water film ultimately reduces the adhesive force. The higher the soil moisture content, the better results can be achieved by electro-osmosis techniques (Fig. 4).

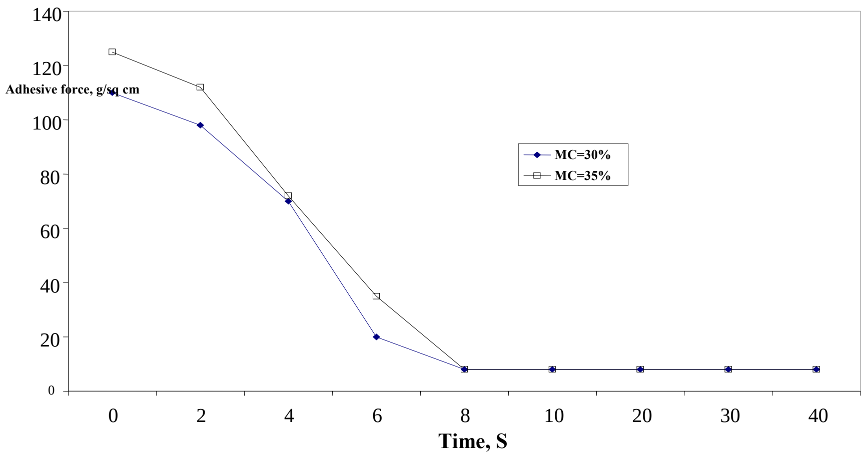

Figure 4: The relationship of adhesive force and electro-osmosis time (derived from Chen *et al*. 1990)

The voltage, electrode distance, and the area of electrode plate all have significant effects on adhesive forces. The application of this technique requires energy. To make it practical in the field situation, the benefits of reducing the adhesive forces have to be greater than the energy spent to achieve them. The experimental model suggested that it is fully feasible for excavators (Chen *et al*. 1993).

2.3.4 Soil scouring by vibration

Vibration can be used in reducing adhesion of soil to the surface of soil engaging components of various machines and tools. Soil contact with tools is reduced when vibration is applied perpendicular to soil-tool interface. This reduces the soil-tool area of contact and let the air and water flow smoothly. This technique is helpful in improving both the lubrication and the soil scouring. Although, it improves scouring characteristics of the tools and machines but has not because practically applied because of the potential damage it may inflict on machine itself. Wang *et al*. (1998) reported that soil adhesion can be reduced by vibration of parts of the machines that come in contact with soil.

2.3.5 Soil scouring by mechanical means

Soil scouring can be improved by making the contact surfaces elastic and flexible. The productivity of shovel improved by 15% when this technique was used to excavate frozen soils (CHEN et al. 1990); chains have been used to improve soil scouring from excavators. Sometimes, the structure becomes too complicated and requires regular service for keeping the system functioning properly. Scraping the soil is commonly used to scour soil from the surfaces of a number of soil engaging components of various machines and tools. This technique is simple to construct, easy to use and requires no extra power. Scarpers are commonly used on tillage and sowing equipment. Wear and tear is a major issue associated with this technique. However, it is more complicated to use scrapers on the surfaces of shovels.

2.3.6 Soil scouring by surface modifications

Soil scouring can be improved by modifying the surface characteristics of soil engaging components of machines and tools. For example, silicon lubricant oil was used in China to improve the scouring properties of wooden plough (Chen *et al*. 1990). Some of the materials such as UHMW-PE, polytetra fluoroethylene (PTFE), polyethylene and porcelain are used for coating the surfaces of mouldboard ploughs (REN et al. 1990). The coefficient of friction of PTFE can be up to 50% less than steel 45. PTFE improves soil scouring and reduces the draft by up to 25% as shown in Table 2 (CHEN et al. 1990). Enamel coating was employed on the surface of mouldboard ploughs to improve soil scouring properties. The draft of enamel coated plough surfaces reduced by 14% and 16% at 3.6 km/h and 4 km/h working speeds respectively (Salokhe *et al*. 1990). In another laboratory experiment, enamel coating on mouldboard plough surface reduced the draft by up to 26%, depending on soil moisture content and working speed (Salokhe *et al*. 1989). Some of these materials have poor wear resistance and practically cannot be used in abrasive soil conditions. For example, PTFE coating of 0.50-0.80 cm thickness lasts for ploughing of 20 ha and high density polyethylene covering of 0.50-0.80 cm lasts for about 8 ha in abrasive soils (Salokhe *et al*. 1990). The higher costs and lower life are the main limiting factors in using these materials practically in the field.

2.3.7 Soil scouring by bionic

The shape and size of the soil engaging components of machinery and equipment have significant effect on soil adhesion. For example, reducing the soil-tool area of contact and unsmoothed surface morphology to discontinue the moisture film at soil-tool interface are helpful in scouring soil. The unsmoothed mouldboard plough surfaces by UHME-PE convexes improved soil scouring and reduced the draft by 25% and 30% at 3.6 km/h and 4 km/h ploughing speeds respectively (Qaisrani 1993). Qaisrani (1993) employed the surface morphology of ground beetle for the modification of mouldboard ploughs and bulldozing plates. The plough and bulldozing plates modified by bionic improved soil scouring and reduced the draft of these implements significantly. The bionic modification of the surfaces of various machines and tools based on the surface morphology of a number soil animals cuticles are simple and can be used in practical field conditions. However, the manufacturing techniques are comparatively complicated unless produced on mass scale.

3. CONCLUSIONS

The paper reviewed some of the methods employed to improve soil scouring properties of soil engaging components of different machines and tools. Each of these techniques has its advantages and disadvantages. However, an ideal technique should be simple, ease to manufacture and use, low cost, synchronised with other components of the machines with no extra controls and power requirements, effective and efficient with scouring rate 90% or higher. No one technique has universal application. Some techniques are better for one system and others are useful for another. Soil adhesion preventing mechanism of soil animal's cuticles can be employed in modifying the surfaces of soil engaging components of a number of machines and equipment. The benefits of research work could be achieved by applying these techniques practically on the surfaces of machines and equipment. The material used for modifications should have better wear resistance for making this technique practical. Some techniques such as enamel coating is simple and cheap but its use cannot be recommended under abrasive soil conditions because of its poor wear characteristics.

The research results of a number of studies showed that the drafts of mouldboard ploughs and bulldozing plates modified by bionic were reduced by improving the soil scouring properties of these implements. However, there have been some inconsistencies in the results mainly because these trials were conducted under varying conditions. It is very difficult to repeat these experiments under similar conditions. Moreover, the operation of a number of soil engaging components of agricultural and industrial machinery is different from that of soil animals. Therefore, for improving the efficiency of these tools, each implement has to be designed differently based on their operating environment. However, the soil adhesion preventing mechanism of soil animals can successfully be used as a guideline for reducing adhesion and scouring soil from the surfaces of various soil engaging components of agricultural and industrials machinery. In some situation a combination of these techniques may be used to achieve the desired outcome.

Table 1: The effect of heat on soil adhesion measured as coefficient of friction (μ) of steel slider on dry sand (Nichols 1931).

Slider weight, g	Slider condition		
	Dry	Wet	Hot
1500	0.266	0.333	0.250
3000	0.266	0.333	0.250
4500	0.266	0.333	0.244

Table 2: Effects of PTFE plough covering on draft (kN) of mouldboard ploughs operating at two different speeds (Chen *et al*. 1990)

Plough surface	*Draft, kN*			
	Decatur clay		*Deviation clay*	
	1.60 km/h	5.6 km/h	1.60 km/h	*5.6 km/h*
Steel (Conventional)	2.00	2.18	2.14	*2.56*
PTFE covered mouldboard with steel share	1.73	2.16	1.89	*2.36*
PTFE covered mouldboard and share	*1.62*	*1.91*	*1.38*	*1.96*

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