Available online at www.sciencedirect.com
ScienceDirect
Soil & Tillage Research 94 (2007) 493–502
Soil & Tillage Research
www.elsevier.com/locate/still

The adoption of annual subsoiling as conservation tillage in dryland maize and wheat cultivation in northern China

He Jin [a], Li Hongwen [a,*], Wang Xiaoyan [a], A.D. McHugh [b], Li Wenying [a], Gao Huanwen [a], N.J. Kuhn [c]

[a] *Department of Agricultural Engineering, China Agricultural University, P.O. Box 46, Beijing 100083, China*
[b] *School of Agronomy and Horticulture, University of Queensland, Gatton, Qld. 4343, Australia*
[c] *Department of Geograohy, University of Exeter, Exeter EX4 4RJ, United Kingdom*

Received 15 January 2006; received in revised form 8 September 2006; accepted 7 October 2006

Abstract

Soil compaction caused by random traffic or repetitive tillage has been shown to reduce water use efficiency, and thus crop yield due to reduced porosity, decreased water infiltration and availability of nutrients. Conservation tillage coupled with subsoiling in northern China is widely believed to reduce soil compaction, which was created after many years of no-till. However, limited research has been conducted on the most effective time interval for subsoiling, under conservation tillage. Data from conservation tillage demonstration sites operating for 10 years in northern China were used to conduct a comparative study of subsoiling interval under conservation tillage. Three modes of traditional tillage, subsoiling with soil cover and no-till with soil cover were compared using 10 years of soil bulk density, water content, yield and water use efficiency data. Cost benefit analysis was conducted on subsoiling time interval under conservation tillage. Yield and power consumption were assessed by based on the use of a single pass combine subsoiler and planter. Annual subsoiling was effective in reducing bulk density by only 4.9% compared with no-till treatments on the silty loam soils of the Loess plateau, but provided no extra benefit in terms of soil water loss, yield increase or water utilization. With the exception of bulk density, no-till and subsoiling with cover were vastly superior in increasing water use (+10.5%) efficiency and yield (+12.9%) compared to traditional tillage methods. Four years of no-till followed by one subsoiling reduced mechanical inputs by 62%, providing an economic benefit of 49% for maize and 209% for wheat production compared to traditional tillage. Annual subsoiling reduced inputs by 25% with an increased economic benefit of 23% for maize and 135% for wheat production. Yield and power consumption was improved by 5% and 20%, respectively, by combining subsoiling with the planting operation in one pass compared with multipass operations of subsoiling and planting. A key conclusion from this is that annual subsoiling in dryland areas of northern China is uneconomical and unwarranted. Four years of no-till operations followed by 1 year subsoiling provided some relief from accumulated soil compaction. However, minimum soil disturbance and maximum soil cover are key elements of no-till for saving water and improving yields. Improved yields and reduced farm power consumption could provide a significant base on which to promote combined planter and subsoiling operations throughout northern China. Further research is required to develop a better understanding of the linkages between conservation tillage, soil quality and yield, aimed at designing most appropriate conservation tillage schemes.

Keywords: Conservation tillage; Subsoiling; No-till; Maize; Wheat; Loess; Economics

* Corresponding author. Tel.: +86 10 62737631; fax: +86 10 62737631.
E-mail address: lhwen@cau.edu.cn (L. Hongwen).

0167-1987/$ – see front matter
doi:10.1016/j.still.2006.10.005

1. Introduction

Conservation tillage uses either minimum-till, or no-till to maximise straw coverage, which can increase soil water content, improve soil structure, thereby reducing soil degradation and erosion. Conservation tillage is effective in increasing yield and water use efficiency (Aase and Pikul, 1995), reducing dust storms and advancing sustainable development of agriculture in the world (CTIC, 1995; Ronald, 1997). In China, funded by the Australian Centre of International Agricultural Research (ACIAR), China Agricultural University and University of Queensland began experimental research on conservation tillage in Shanxi province in 1991 (Gao et al., 2000). The results of the 10-year conservation tillage study demonstrated about 10% increase in crop yield, and a 20% reduction in operation costs in northern China (Li et al., 2000a; Gao et al., 2003). Gao et al. (1999), Wang et al. (2000, 2001) established that compared with traditional tillage, conservation tillage could increase water use efficiency by 11% and reduce soil water erosion by 52% and decrease soil loss by 80% on sloping farmland ($<5^{\circ}$). The adoption of conservation tillage cropping systems also has been associated with increased crop yield and water use efficiency in northern China by Zhou et al. (2001), Liao et al. (2002), Li et al. (2005), and Xue et al. (2005).

In the absence of cultivation, long-term no-till farming can cause soil compaction. Hill (1990) tested soil strength, which is the important index of soil compaction, under long-term no-till system and found two to five times higher penetration resistances within the 0.16 m depth under continuous no-till cultivation compared to conventional plow tillage. Soil compaction can adversely affect root growth, uptake of water and nutrients and crop yield according to Etana and Hakansson (1994), Tijink and Van (2000), Nidal and Abu (2003), and Guo (2005a). Adverse effects can be reduced by subsoiling, aimed at breaking compacted layers underneath the plow layer and increasing porosity of the A horizon. Subsoiling was shown by Pikul and Aase (1999) and Joseph and Kristian (2003) to be a key component of conservation tillage, by improving soil structure, reducing soil strength, eliminating soil compaction and increasing yield and water use efficiency. Reeder et al. (1993) evaluated five subsoiler types operated at the 0.3 m depth in 1990. Porosity and cone penetration measurements showed continuing benefits, from all types of subsoilers, 2 years after tillage. Ibrahim et al. (2004) established that subsoiling treatments created statistically significant effects on the soil resistance compared with control plots where subsoiling was not applied. Gao and Li (1995) also indicated that subsoiling reduced soil bulk density by 0.1 Mg/m^3 and increased water content by 11.2% to a depth of 0–50 cm compared with traditional tillage. Ide et al. (1987) found that subsoiling resulted in a mean yield increase of 5–10% for cereals and sugar beet on a silt loam soil through the removal of a plough pan. While Meng et al. (2000) found that subsoiling increased maize yield by 5.7–11.3%.

To resolve the problem of soil compaction and increase crops outputs, Chinese scientists have concentrated on subsoiling techniques. For example, Li and Gao (1997) compared traditional tillage, no-till with cover and subsoiling with cover in arid areas. Wang et al. (2003) studied the effect of subsoiling yields of wheat and maize, and Guo (2005b) investigated soil loosening mechanisms by differing subsoiling components. Kong et al. (2004) researched structural characteristics of existing subsoilers, technical characteristics and field adaptability using various levels of straw cover. These research results and others have made a positive impact on accelerating the development and extension of subsoiling techniques. Although only a limited amount of research on subsoiling has been conducted over a very short period in China, annual subsoiling has been adopted widely to improve soil structure. Prominent techniques include inter-row subsoiling after maize seedling emergence. The practice has introduced increased power consumption, lowered economic benefits, and caused seedling damage, and thus has an adverse impact on the further development and extension of subsoiling techniques. Pre-plant subsoiling has also caused significant problems with seed set and germination.

These problems have been known for some time. Since 1993 an ACIAR project and a Ministry of Agriculture (MOA) conservation tillage demonstration project, have had demonstration sites to conduct experimental research on subsoiling techniques for conservation tillage in northern China. This long-term project investigated the impact conservation tillage and subsoiling, with a particular focus on the frequency of subsoiling required for maintaining yields and improving water use efficiency in the most economic way.

2. Materials and methods

This study is based on largely unpublished data from a comparative experiment of traditional tillage, subsoiling with soil cover and no-till with soil cover conducted on the Loess plateau at Shouyang and Linfen, Shanxi province and on the Huabei Plain at

Fig. 1. Location of ACIAR and MOA demonstration study sites.

Dingxing, Hebei province (Fig. 1). Previously the data from the Loess plateau experiment were reported briefly and in simplistic terms as an assessment of conservation tillage (Gao et al., 2003; Li et al., 2000b). The data from Huabei plain was reported in a recent dissertation at China Agricultural University (Liu, 2004) and was combined with the results of the above experiment and reanalysed in the context of this study.

2.1. Sites

Shouyang County (Fig. 1) is in a semi-humid region at 1100 m above sea level. Average annual temperature is 7.3 °C with 120–140 frost free days. Average annual rainfall of 450–580 mm, occurs in summer, growing a single maize crop per year on Chestnut–Cinnamon Loess soil, low in organic matter (<1%) and slightly alkaline (pH 7.6). According to the USDA texture classification system, the soils are defined as silt loam and according to the FAO-UNESCO soil map (FAO-UNESCO, 1974) the soil type is a Chromic Cambisol.

Linfen is also located in semi-arid and semi-humid region. The average annual temperature is 10.7 °C with 180 frost free days. A single wheat crop is grown with an average annual rainfall of 555 mm per year on Cinnamon Loess soil, low in organic matter (<1%) and slightly alkaline (pH 7.7). Under the USDA texture classification system, the soils are defined as silt loam and according to the FAO-UNESCO soil map (FAO-UNESCO, 1974) the soil type is a Chromic Cambisol. The soils of the Loess plateau are generally described as porous and homogenous to considerable depth with limited variance across fields.

2.2. Experimental design

The comparative experiment conducted in Shouyang and Linfen from 1993 to 2000 consisted of three treatments: traditional tillage, subsoiling with soil cover and no-till with soil cover. Traditional tillage included mouldboard ploughing without residue cover. Subsoiling with soil cover consisted of subsoiling after harvesting in autumn, and no-till planting with maximum soil cover from standing stubble and plant residue on the soil surface (>30%). No-till with soil cover consisted of no-till planting through the plant residue. The comparative experiment used a subsoiler with adjustable wings designed by China Agricultural University in 1992 (Li et al., 2000b) (Fig. 2). The machine is comprised of an anti-blocking disk, a soil levelling device and subsoiling tool with adjustable wings. The front anti-blocking disk cuts crop residues in the subsoiling line, which reduces blockage about the tine. The subsoiling tool, with two symmetrical wings, loosens soil on a large scale without soil inversion and effectively lowers soil bulk density. The maize varieties used at Shouyang were Yandan 14 and Jindan 42. The wheat varieties at Linfen were Jinmai 47 and Linfen 225.

The impact of subsoiling was assessed by changes in bulk density, water content, yield, and water use efficiency. For bulk density and soil moisture measurements, soil samples, collected into steel tubes (54 mm × 75 mm) using a sliding hammer operated soil corer, were taken after harvest to determine bulk density and water content. Soil cores were immediately

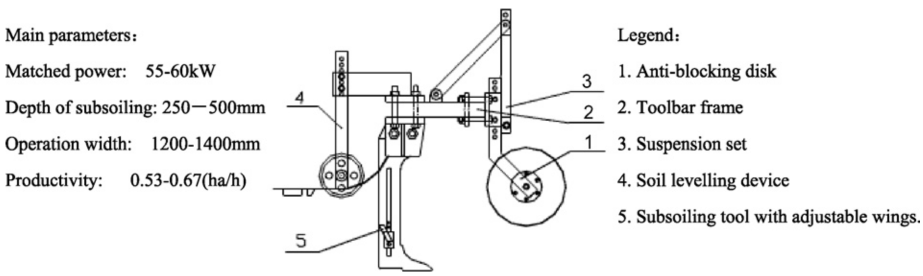

Fig. 2. Schematic diagram of the CAU designed subsoiler with adjustable wings and implement characteristics.

removed from the tube, wrapped in plastic wrap, sealed in a plastic zip lock bag and stored in an aluminium box. The bulk density and water content were determined on a soil oven-dry mass basis by drying 12 mm soil slices from each core, in a fan-aided oven set at 105 °C for 48 h.

Evapotranspiration (ET) was calculated using the formula:

$$\mathrm{ET} = \mathrm{Rainfall} + \mathrm{Total\ irrigation} + \Delta W \quad (1)$$

ΔW is the soil water change (final minus initial), which was calculated by subtracting the total soil water content at 100 cm depth of soil profile determined during the calculated period.Total water use efficiency (WUE) was estimated: the yield produced per m^3 total water used:

$$\mathrm{WUE} = \frac{\mathrm{Yield}}{\mathrm{ET}} \quad (2)$$

The economic benefit of different tillage modes was also assessed during the experiment. Costs were derived from local market conditions and common sources of farming inputs. Common labour charges used in these areas were used to assess further input costs.

2.3. Statistical analysis

Mean values, standard deviations (S.D.) and standard errors (S.E.) were calculated for each of the measurements, and ANOVA was used to assess the effects of tillage on the measured variables. When ANOVA indicated a significant F-value, multiple comparisons of annual mean values were performed by the least significant difference method (LSD). The SPSS analytical software package (2003) was used for all of the statistical analyses.

3. Results

3.1. Soil bulk density

Soil bulk density was used as a significant indicator of changed soil structure and water retention capability under different tillage modes during a long-term project (1992–2000) in Shouyang and Linfen, Shanxi province. At the start of the experiment (after harvesting in 1992), the soil bulk density at Shouyang under all tillage modes was 1.21 Mg/m^3, while at Linfen it was higher, approximately 1.37 Mg/m^3 under all tillage modes. Table 1 shows the range of soil bulk density values found under the three different tillage modes to depth 30 cm from 1993 to 2000.

In the maize experimental plots at Shouyang, the average soil bulk density from 1993 to 2000 for each tillage mode of traditional tillage (TT), subsoiling with soil cover (SSWC) and no-till with soil cover (NTWC) were 1.23 Mg/m^3, 1.28 Mg/m^3, 1.35 Mg/m^3. Except for 1996, soil bulk density for TT and SSWC did not have a significant difference, but NTWC had the highest soil bulk density in all the experimental years, especially in the end years of 1998, 1999 and 2000, indicating that the cumulative effect of traffic caused a significant increase in bulk density in the no-till treatments, but traditional tillage and subsoiling treatments, although affected by cumulative compaction, tended to minimise increased bulk density in the latter half of the experimental period.

Table 1
Mean bulk density (Mg/m^3) to depth of 30 cm for different tillage modes: traditional tillage (TT), subsoiling with soil cover (SSWC) and no tillage with soil cover (NTWC)

Crop	Tillage mode	Year							
		1993	1994	1995	1996	1997	1998	1999	2000
Maize (Shouyang)	TT	1.17^{a}	1.20^{a}	1.14^{a}	1.16^{a}	1.31^{a}	1.29^{a}	1.31^{a}	1.28^{a}
	SSWC	1.19^{ab}	1.28^{ab}	1.19^{a}	1.24^{b}	1.34^{a}	1.34^{a}	1.37^{a}	1.31^{a}
	NTWC	1.27^{b}	1.29^{b}	1.27^{b}	1.28^{b}	1.37^{a}	1.44^{b}	1.46^{b}	1.45^{b}
	S.D. (total)	0.11	0.09	0.09	0.08	0.08	0.11	0.11	0.11
	S.E. (total)	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02
Wheat (Linfen)	TT	1.24^{a}	1.22^{a}	1.24^{a}	1.23^{a}	1.25^{a}	1.29^{a}	1.31^{a}	1.30^{a}
	SSWC	1.34^{b}	1.29^{a}	1.32^{ab}	1.33^{b}	1.37^{b}	1.38^{ab}	1.36^{ab}	1.35^{a}
	NTWC	1.37^{b}	1.38^{b}	1.39^{b}	1.39^{b}	1.42^{b}	1.45^{b}	1.42^{b}	1.43^{b}
	S.D. (total)	0.09	0.11	0.12	0.11	0.11	0.11	0.09	0.10
	S.E. (total)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Samples were taken immediately after harvest during 1993–2000 at Shouyang and Linfen. S.D.: standard deviation; S.E.: standard error. Means within a column followed by the same letters are not significantly different ($P = 0.05$).

Table 2
Mean volumetric water content (cm^3 cm^{-3}) to depth of 30 cm for different tillage modes: traditional tillage (TT), subsoiling with soil cover (SSWC) and no tillage with soil cover (NTWC)

Crop	Tillage mode	Year								
		1992	1993	1994	1995	1996	1997	1998	1999	2000
Maize (Shouyang)	TT	13.7^{a}	13.6^{ab}	16.7^{a}	15.6^{a}	17.8^{a}	18.1^{a}	10.7^{a}	7.2^{a}	8.4^{a}
	SSWC	13.8^{a}	13.5^{a}	18.9^{b}	16.7^{b}	19.6^{b}	18.7^{b}	10.7^{a}	8.4^{b}	8.9^{b}
	NTWC	13.7^{a}	14.2^{b}	18.4^{b}	17.1^{b}	19.3^{b}	18.4^{ab}	10.4^{a}	8.9^{b}	9.1^{b}
	S.D. (total)	0.77	0.72	1.30	0.93	1.15	0.56	0.57	0.95	0.58
	S.E. (total)	0.14	0.13	0.24	0.17	0.21	0.10	0.10	0.17	0.11
Wheat (Linfen)	TT	12.8^{a}	13.0^{a}	11.4^{a}	14.2^{a}	9.0^{a}	15.7^{a}	17.9^{a}	15.1^{a}	16.2^{a}
	SSWC	12.8^{a}	13.7^{b}	11.7^{ab}	16.8^{b}	10.8^{b}	17.3^{b}	18.6^{a}	15.5^{a}	17.0^{b}
	NTWC	12.8^{a}	13.1^{a}	12.0^{b}	17.1^{b}	10.6^{b}	17.6^{b}	17.7^{a}	15.0^{a}	16.8^{ab}
	S.D. (total)	0.42	0.59	0.59	1.42	0.96	1.11	0.93	0.86	0.74
	S.E. (total)	0.08	0.11	0.11	0.26	0.18	0.20	0.17	0.16	0.13

Samples were taken immediately after harvest during 1992–2000 at Shouyang and Linfen. S.D.: standard deviation; S.E.: standard error. Means within a column followed by the same letters are not significantly different ($P = 0.05$).

In the wheat experimental plots of Linfen, the mean soil bulk density of 1993–2000 in TT, SSWC, NTWC were 1.26 Mg/m^3, 1.34 Mg/m^3, 1.41 Mg/m^3, and TT and NTWC showed the lowest and highest soil bulk density, respectively. During the experimental years, with ploughing or annual deep tillage, soil bulk density for TT and SSWC changed from year to year and was generally stable over the 7 years. Soil bulk density for NTWC was also stable but remained at significantly high levels compared to the other treatments for the duration of the experiment. Therefore, in maize and wheat production systems, tillage was effective in reducing the effects of compaction by maintaining lower bulk density levels compared to no-till treatments.

3.2. Water content

Table 2 shows the volumetric water content to a depth of 30 cm following harvest from 1992 to 2000 for the three tillage modes at Shouyang and Linfen. At the beginning of the experiment (following maize and wheat harvest in 1992), volumetric water content of Shouyang and Linfen in traditional tillage, subsoiling with soil cover and no-till with soil cover were not significantly different (Table 2).

As indicated in Table 2, subsoiling with soil cover and no-till with soil cover reduced soil moisture loss compared to traditional tillage during the 9 years from 1992 to 2000. In Shouyang, soil moisture of no-till with soil cover was 5% higher than that of traditional tillage in 75% of years, and the differences in 5 out of 8 years were significant. The subsoiling treatment moisture content was 5% greater than that of traditional tillage in 50% of years, and the differences in 6 out of 8 years were significant. Maximum difference between traditional tillage and the soil cover treatments was 10–12% in 1994.

In Linfen under wheat, the covered treatments conserved more than 5% water than traditional tillage in 50% of years and the differences in about 5 out of 8 years were significant. However, the maximum difference between covered treatments and traditional tillage was 16–17% in 1996 and 1995, respectively. Therefore, as soil disturbance increased, soil moisture losses also increased. Under traditional tillage, farmers would have to wait for considerably more rainfall to fill the soil profile compared with other soil management methods which include soil cover and low soil disturbance and thus require less rainfall because of smaller evaporation and runoff losses.

3.3. Crop yield

Yields of the maize and wheat in both districts, in all tillage modes, fluctuated widely from year to year generally because of the different climatic conditions in each year (Table 3). Generally speaking, from 1993 to 2000, the yields for subsoiling with soil cover and no-till with soil cover treatments were slightly higher than traditional tillage yields, but without significant differences at $P = 0.05$ in most years. The trend, over the 8 years, indicated that subsoiling with soil cover and no-till with soil cover were 10–12% higher in both Shouyang and Linfen compared to traditional tillage. However, wheat tended to perform consistently better under no tillage and subsoiling treatments, whereas the maize yields were very similar across all tillage modes, due to the differences in root systems and their performances under compacted soil conditions.

Table 3
Mean yield (t/ha) for different tillage modes: traditional tillage (TT), subsoiling with soil cover (SSWC) and no tillage with soil cover (NTWC), in Shouyang and Linfen from 1993–2000

Crop	Tillage mode	Year							
		1993	1994	1995	1996	1997	1998	1999	2000
Maize (Shouyang)	TT	2.6[a]	6.7[a]	4.4[a]	4.9[a]	4.3[a]	7.2[a]	3.7[a]	4.1[a]
	SSWC	3.5[b]	8.2[b]	4.8[a]	4.8[a]	5.0[a]	8.3[a]	3.7[a]	4.5[a]
	NTWC	3.1[ab]	8.5[b]	5.3[a]	5.1[a]	4.6[a]	8.2[a]	3.9[a]	4.4[a]
	S.D. (total)	0.50	0.95	0.59	0.43	0.43	0.74	0.32	0.36
	S.E. (total)	0.17	0.32	0.20	0.14	0.14	0.25	0.11	0.12
Wheat (Linfen)	TT	2.6[a]	3.0[a]	2.3[a]	3.5[a]	3.8[a]	2.3[a]	2.2[a]	2.3[a]
	SSWC	2.9[a]	3.3[a]	2.3[a]	3.8[a]	4.0[a]	2.8[a]	2.6[ab]	2.7[a]
	NTWC	2.8[a]	3.6[a]	2.7[a]	4.0[a]	4.0[a]	2.7[a]	2.7[b]	2.6[a]
	S.D. (total)	0.32	0.39	0.31	0.36	0.47	0.38	0.35	0.28
	S.E. (total)	0.11	0.13	0.10	0.12	0.16	0.13	0.12	0.09

S.D.: standard deviation; S.E.: standard error. Means within a column followed by the same letters are not significantly different ($P = 0.05$).

3.4. Water use efficiency

The water use efficiency was assessed in the experimental plots at Shouyang and is shown in Table 4.

Table 4 shows that the discrepancy of average water use efficiency between no-till with soil cover and subsoiling with soil cover was slight in Shouyang. However, both of the values were higher than traditional tillage and the differences between covered treatments and traditional tillage treatment were significant in about 5 out of 8 years ($P = 0.05$).

No-till with soil cover reduced soil water loss through high standing stubble and straw cover, whereas annual subsoiling with soil cover caused irregularities of soil surface and along with soil disturbance, and increased soil water loss to the atmosphere (Yao et al., 2002). The water saving under no-till with soil cover tended to enhance water use efficiency by 1.5% from 1993 to 2000 in Shouyang (Table 4) compared to subsoiling treatments. In most years, as expected with maximum soil disturbance, traditional tillage was considerably less efficient in converting available water into yield.

3.5. Economic benefit

The sites at Shouyang and Linfen were used to analyse the economic benefit of different tillage modes for maize and wheat in northern China. The agronomic input costs and mechanical operation costs are shown in Table 5. The agronomic costs refer to expenses such as; seed, fertiliser, herbicide, salary and taxes. The mechanical operation costs include fuel, oils, salary, maintenance, depreciation and administration expense. Outputs refer to grain yield in kg/ha and income received in US$.

Economic cost benefit analyse indicates that annual subsoiling and no-till with subsoiling once in 4 years are vastly superior options than traditional tillage (Table 5). Field operations (mechanical inputs) were reduced by 62.5% and 25% in 4-year no-till plus 1-year subsoiling and annual subsoiling, respectively. Maize yield were also improved under these treatments and improved farmer profit by 49% and 21%, respectively.

The economic benefit of no-till and subsoiling for wheat production was similar, in that profit from

Table 4
Mean water use efficiencies (kg ha^{-1} mm^{-1}) for maize under three different tillage modes: traditional tillage (TT), subsoiling with soil cover (SSWC) and no-till with soil cover (NTWC) in Shouyang

Tillage	Year							
	1993	1994	1995	1996	1997	1998	1999	2000
TT	6.3[a]	10.8[a]	8.1[a]	8.6[a]	8.0[a]	10.2[a]	8.4[a]	7.9[a]
SSWC	8.3[b]	12.2[b]	8.6[a]	8.5[a]	8.6[b]	12.2[b]	8.4[a]	8.2[a]
NTWC	8.3[b]	12.3[b]	9.4[b]	8.8[a]	8.4[b]	12.2[b]	8.5[a]	8.2[a]
S.D. (total)	1.00	0.76	0.65	0.30	0.32	1.02	0.21	0.21
S.E. (total)	0.33	0.25	0.22	0.10	0.11	0.34	0.07	0.07

S.D.: standard deviation; S.E.: standard error. Means within a column followed by the same letters are not significantly different ($P = 0.05$).

Table 5
Economic cost benefit analysis of three tillage modes: traditional tillage, annual subsoiling with soil cover and no tillage with cover plus subsoiling once in 4 years for maize and wheat production in Shouyang and Linfen regions of Shanxi province

	Traditional tillage		Annual subsoiling with soil cover		Four-year no-till with cover + 1 year subsoiling	
	Maize	Wheat	Maize	Wheat	Maize	Wheat
Inputs						
Seed (US$/ha)	28	84	28	84	28	84
Fertiliser (US$/ha)	75	87.5	75	87.5	75	87.5
Herbicide (US$/ha)	5.6	3.8	5.6	3.8	5.6	3.8
Salary (US$/ha)	85	62.5	70	46.9	70	46.9
Mechanical operation cost (US$/ha)	75	125	56	87.5	28	62.5
Taxes (US$/ha)	75	56	75	56	75	56
Total	343.6	418.8	309.6	365.7	281.6	340.7
Outputs						
Yield[a] (t/ha)	4.652	3.041	4.820	3.273	5.095	3.439
Price (US$/kg)	0.125	0.163	0.125	0.163	0.125	0.163
Income (US$/ha)	581.5	491.3	602.5	533.5	636.9	560.6
Farmer income (US$/ha)	237.9	72.5	292.9	167.8	355.3	219.9
Incremental improvement on traditional tillage (%)			23.0	135.3	49.3	209.2

[a] The data are the average values of yields from 1993 to 1996.

traditional tillage, subsoiling with soil cover, and 4-year no-till with cover plus 1-year subsoiling were US$ 72.5 ha^{-1}, US$ 167.8 ha^{-1} and US$ 219.9 ha^{-1}, respectively. Mechanical operation costs were reduced by 50.0%, 29.0% and outputs increased by 14.0% and 5.0% compared with traditional tillage.

4. Discussion

No-till farming practice from 1993 to 2000 was effective in increasing crop yield and water use efficiency in Shouyang and Linfen compared to subsoiling with soil cover and traditional tillage (Tables 3 and 4), similar to the findings of Lopez and Arrue (1997). The significant contribution can be explained by improved soil physical properties (Ehlers and Claupein, 1994) and greater soil moisture (Izaurralde et al., 1986).

Subsoiling can loosen the soil and eliminate soil compaction under many years no-till farming. However, because no-till had less traffic effect in the first several years, the effect of annual subsoiling to bulk density was inconspicuous. In our case, mean soil bulk densities of SSWC, NTWC from 1993 to 1996 were 1.23 Mg/m^3, 1.26 Mg/m^3 in Shouyang and 1.32 Mg/m^3 and 1.37 Mg/m^3 in Linfen. These values indicate that the difference between SSWC and NTWC was not significant during the first 4 years (Table 1). From 1997 to 2000, NTWC

Table 6
Mean water use efficiencies (kg ha^{-1} mm^{-1}) and yields (t/ha) for maize and wheat under three different tillage modes: traditional tillage (TT), subsoiling with soil cover (SSWC) and no-till with soil cover (NTWC) in Dingxing (Liu, 2004)

Crop	Tillage mode	Yield (t/ha)						Water efficiency (kg ha^{-1} mm^{-1})					
		2002			2003			2002			2003		
		Mean	S.D.	S.E.	Mean	S.D.	S.E.	Mean	S.D.	S.E.	Mean	S.D.	S.E.
Maize	TT	8.7[a]	0.55	0.32	8.3[a]	0.50	0.29	22.0[a]	0.76	0.44	20.8[a]	0.81	0.47
	SSWC	8.9[a]	0.60	0.35	9.4[b]	0.60	0.35	22.3[a]	0.65	0.38	22.6[b]	0.68	0.39
	NTWC	9.5[a]	0.60	0.35	10.3[b]	0.50	0.29	23.1[a]	0.51	0.30	23.3[b]	0.70	0.41
Wheat	TT	4.1[a]	0.42	0.24	4.8[a]	0.40	0.23	15.1[a]	0.42	0.24	18.1[a]	0.61	0.35
	SSWC	4.3[a]	0.45	0.26	5.1[a]	0.53	0.31	15.6[a]	0.53	0.31	18.6[a]	0.47	0.27
	NTWC	4.7[a]	0.44	0.25	5.2[a]	0.53	0.31	18.2[b]	0.47	0.27	20.1[b]	0.55	0.32

S.D.: standard deviation; S.E.: standard error. Means within a column followed by the same letters are not significantly different ($P = 0.05$).

bulk density values diverged significantly from the other tillage values because of the cumulative traffic effect, stabilizing within the range of 1.37–1.46 Mg/m^3 in Shouyang and 1.42–1.45 Mg/m^3 in Linfen. While annual subsoiling could minimise increased bulk density through loosening soil, but it was not effective in restoring bulk density to pre-1993 values.

The application of annual subsoiling offered little benefit to soil moisture during the experimental year from 1992 to 2000 compared to no-till (Table 2). In a comparison of subsoiling with soil cover and no-till with soil cover in experimental wheat plots, in 5 out of 8 years there was a slight benefit in terms of increased soil moisture, thereinto, only the benefit in 1993 was significant. In the maize plots at Shouyang, compared to no-till treatments with cover, subsoiling with soil cover did not change much, the only significant improvement of soil moisture by subsoiling was observed in 1993.

The results indicate that subsoiling had a strong effect in the first year. This is consistent with a 3-year subsoiling experiment conducted in the upper Midwest region of the USA near Morris, which indicated that annual subsoiling had very little effect on soil moisture content over three cropping seasons (Evans et al., 1996). Annual subsoiling thus provided little benefit during the first several years under long-time no-till farming. A similar result was found in 2 years of data in 2002 and 2003 on the Huabei Plain at Dingxing, Hebei province (Table 6), where maize and wheat yields and water use efficiencies were not significantly influenced by subsoiling, but traditional tillage plots did yield and water use efficiency less than the soil covered treatments (Liu, 2004). However, after 1997, because increasing soil compaction after continuous no-till limited the development of root and movement of water and nitrogen, the yield and water use efficiency advantages of no-till with soil cover were slight at the end of experimental years compared to subsoiling with soil cover. So after 4 or 5 years of continuous no-till, 1-year subsoiling could be used to decrease soil bulk density, improve soil structure and retain the high yield of conservation tillage as opposed to annual subsoiling.

These results suggest that, in terms of soil bulk density (compaction), available soil water, yield and water utilization, under conservation tillage, subsoiling with cover could resolve soil compaction, which usually appears under continuous no-till and minimum-till operations. However, annual subsoiling did not improve soil water content, yield or water use efficiency to any marked degree, compared to no-till with soil cover in the first 4 years of the tests. Therefore, a new tillage mode of 4-year no-till coverage plus 1-year subsoiling is proposed. This new tillage mode could solve soil water loss and low water use efficiency issues that have existed after many years of traditional tillage and soil compaction accumulation under minimum-till and no-till operations. More importantly, its economic returns to the farmers were considerable (Table 5). This form of conservation tillage in northern China could be a significant improvement on current practice and the economic analysis alone should be enough to promote the widespread adoption of no-till, with soil cover and subsoiling once every 4 years.

Ideally, subsoiling should be combined with no-till seeding, reducing wheel trafficking and energy input. A study conducted in Zhangqiu, Shandong province and Daxing, Beijing by He et al. (2004) showed that by integrating maize no-till seeding and subsoiling into a single pass operation, a saving of 20% in power consumption is possible (Fig. 3). Because of better seed set and no damaging to maize seedling, combined operations improved yields by 5.8% and 4.2% in Zhangqiu and Daxing compared to sole operation,

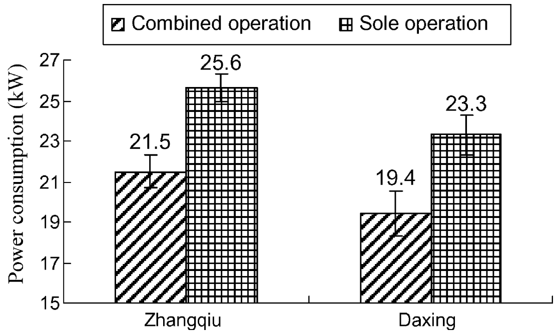

Fig. 3. Power consumption of a combined planting and subsoiling operation compared with sole planting and subsoiling operations for maize at Zhangqiu and Daxing.

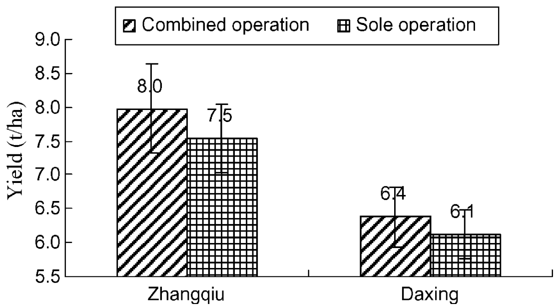

Fig. 4. Comparison of autumn maize yields for combined planting and subsoiling and sole operations of planting and subsoiling in Zhangqiu and Daxing regions of the Huabei plain.

respectively (Fig. 4). These results indicated the combined method of planting and subsoiling of no-till maize, which used less power, fuel and time in the field, and had higher yield, could provide considerable benefits to the new tillage mode of 4-year no-till coverage plus 1-year subsoiling.

5. Conclusions

A key result of this study is that the practice of annual subsoiling is unwarranted in northern China. The tillage mode most suited to current conservation tillage practices appears to be a 4-year no-till planting operation (maintaining soil cover), plus 1-year subsoiling to minimise compaction caused by random wheel traffic. By adopting a 4-year no-till plus 1-year subsoiling farmer incomes for maize production can be improved by 49% in comparison to incomes from traditional tillage methods.

Should subsoiling be necessary a more effective and efficient method such as combined planter and subsoiler should be adopted. The novel machine can reduce tractor power consumption by 20% and add about 5% to maize yields.

While the results of this long-term study demonstrate that annual subsoiling is unwarranted and uneconomical in northern China, the development of effective subsoiling schedules requires more research on soil sensitivity to compaction and the relationships between tillage practices, soil quality and yields. In particular, further assessment of the impact of random field traffic and its management is required, because no-till operations increased soil compaction and subsoiling was ineffectual in removing it.

Acknowledgements

Many thanks to the Shanxi Agricultural Mechanization Management Bureau, for their support and thanks to Dr. Jeff Tullberg and Mr. Ross Murray for their work in implementing the ACIAR project in China. Also thanks to all the postgraduate students working in Conservation Tillage Research Centre, MOA, who provided their input to this study.

References

Aase, J.K., Pikul, J.L., 1995. Crop and soil response to long-term tillage practices in the northern Great Plains. Agron. J. 87, 652–656.

CTIC, 1995. Conservation Impact, vol. 12. Conservation Technology Information Center, pp. 1–6.

Ehlers, W., Claupein, W., 1994. Approaches towards conservation tillage in Germany. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agroecosystems. Lewis Publishers, Boca Raton, USA, pp. 141–165.

Etana, A., Hakansson, I., 1994. Swedish experiments on the persistence of subsoil compaction caused by vehicles with high axle load. Soil Till. Res. 29, 167–172.

Evans, S.D., Lindstrom, M.J., Voorhees, W.B., Moncrief, J.F., Nelson, G.A., 1996. Effect of subsoiling and subsequent tillage on soil bulk density, soil moisture, and corn yield. Soil Till. Res. 38, 35–46.

FAO-UNESCO, 1974. Soil Map of the World. UNESCO, Paris.

Gao, H.W., Li, H.W., 1995. A testing study of dryland subsoiling. Agric. Res. Arid Areas 4, 126–133 (in Chinese).

Gao, H.W., Li, H.W., Chen, J.D., 1999. Research on sustainable mechanized dryland farming. Agric. Res. Arid Areas 1, 57–62 (in Chinese).

Gao, H.W., Li, H.W., Chen, J.D., 2000. Sustainable mechanized dry land farming research in Northern China [C]. In: ISTRO International Conference, Fort Wort, Texas, USA, pp. 2–5.

Gao, H.W., Li, W.Y., Li, H.W., 2003. Conservation tillage technology with Chinese characteristics. Trans. CSAE 3, 1–4 (in Chinese).

Guo, X.R., 2005a. Application study on technique of the soil deep loosening. J. Shanxi Agric. Univ. 1, 74–77 (in Chinese).

Guo, X.R., 2005b. Comparative study on mechanism of multi-subsoiler deep loosening the soil. J. Agric. Mechanization Res. 3, 78–80 (in Chinese).

He, J., Li, H.W., Mao, N., Wang, S.D., 2004. Experimental study on combined operation of drilling and subsoiling for no-till maize. In: The 2004 CIGR International Conference, Beijing, China, October, pp. 188–193.

Hill, R.L., 1990. Long term conventional and no-tillage effects on selected soil physical properties. Soil Sci. Soc. Am. J. 54, 161–166.

Ibrahim, A., Engin, C., Mehmet, T., Murad, C., Onal, I., 2004. The effect of subsoiling on soil resistance and cotton yield. Soil Till. Res. 77, 203–210.

Ide, G., Hofman, G., Ossemerct, C., Van, R.M., 1987. Subsoiling time dependency of its beneficial effects. Soil Till. Res. 10, 213–223.

Izaurralde, R.C., Hobbs, J.A., Swallow, C.W., 1986. Effects of reduced tillage practices on continuous wheat production and on soil properties. Agron. J. 78, 787–791.

Joseph Jr., L., Kristian, J.S., 2003. Water infiltration and storage affected by subsoiling and subsequent tillage. Soil Sci. Soc. Am. J. 3, 859–866.

Kong, D.J., Wang, S.X., Gao, H.W., 2004. Research on loosening implements under conservation tillage. J. Agric. Mechanization Res. 1, 184–196 (in Chinese).

Li, H.W., Chen, J.D., Deng, J., Zhao, W.D., 2000a. Study on technology and machines of mechanized conservation tillage for dryland maize. J. China Agric. Univ. 4, 68–72 (in Chinese).

Li, H.W., Chen, J.D., Li, W.Y., 2000b. Study on subsoiling technique for conservation tillage field. Trans. Chin. Soc. Agric. Machinery 6, 42–45 (in Chinese).

Li, H.W., Gao, H.W., 1997. A comparison of three tillage methods in dryland farming. Agric. Res. Arid Areas 1, 7–11 (in Chinese).

Li, L.L., Huan, G.B., Jin, X.J., 2005. Effects of conservation tillage on soil water regimes in arid areas. Acta Ecol. Sin. 9, 2326–2332 (in Chinese).

Liao, Y.C., Han, S.M., Wen, X.X., 2002. Soil water content and crop yield effects of mechanized conservative tillage-cultivation system for dryland winter wheat in the Loess tableland. Trans. CSAE 4, 68–71 (in Chinese).

Liu, L.J., 2004. Systematic experiments and effect analysis of all year conservation tillage in two crops a year region. Ph.D. Dissertation. China Agricultural University, Beijing, China (in Chinese).

Lopez, M.V., Arrue, J.L., 1997. Growth, yield and water use efficiency of winter barley in response to conservation tillage in a semi-arid region of Spain. Soil Till. Res. 44, 35–54.

Meng, Q.Q., Xie, J.G., Hu, H.J., 2000. Effect of deep tillage of soil to maize yield and it's component factors. J. Jilin Agric. Sci. 2, 25–28 (in Chinese).

Nidal, H., Abu, H., 2003. Compaction and subsoiling effects on corn growth and soil bulk density. Soil Sci. Soc. Am. J. 4, 1213–1219.

Pikul, J.L., Aase, J.K., 1999. Wheat response and residual soil properties following subsoiling of a sandy loam in eastern Montana. Soil Till. Res. 51, 61–70.

Reeder, R.C., Wood, R.K., Finck, C.L., 1993. Five subsoiler designs and their effects on soil properties and crop yields. Trans. ASAE 6, 1525–1531.

Ronald, B.H., 1997. Long-term conservation tillage studies: impact of no-till on seed corn maggot. Crop Prot. 3, 221–225.

Tijink, F.J., Van, J.P., 2000. Engineering approaches to prevent subsoil compaction in cropping systems with sugar beet. In: Horn, R., van den Akker, J.J.H., Arvidsson, J. (Eds.), Subsoil Compaction. Advances in Geoecology, vol. 32. Catena Verlag, Reiskirchen, pp. 442–452.

Wang, T.C., Li, X.M., Sui, R.T., 2003. A primary study on the technical effects of subsoiling in row space at corn seedling growth stage. Chin. Agric. Sci. Bull. 4, 40–43 (in Chinese).

Wang, X.Y., Gao, H.W., Du, B.M.N., 2001. Rainfall infiltration related to different conservation tillage factors. J. China Agric. Univ. 6, 42–47 (in Chinese).

Wang, X.Y., Gao, H.W., Li, H.W., Zhou, X.X., 2000. Experimental study on runoff and erosion under conservation tillage. Trans. ASAE 3, 66–69 (in Chinese).

Xue, S.P., Yan, Q., Zhu, R.X., Wang, H.Q., Yao, W.S., 2005. Experimental study on conservation tillage technology of complete corn stalk cover by mechanization and furrow sowing beside film mulching. Trans. CSAE 7, 81–83 (in Chinese).

Yao, Y.Q., Nu, J.J., Wang, Y.H., Huang, J.T., 2002. Effect of conservation tillage on yield and benefit of winter wheat in dry-land in west Henan. Agric. Res. Arid Areas 4, 42–44 (in Chinese).

Zhou, X.X., Gao, H.W., Liu, X.F., 2001. Experimental study on conservation tillage system in areas of two crops a year in north China plain. Trans. CSAE 6, 81–84 (in Chinese).