Conservation tillage and nutrient management in dryland farming in China

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Abstract

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Northern China has a large dryland area. Rainfed maize and wheat are the main cereals grown here, accounting for 28% of China's cereal production. Crop yields are constrained by low and variable rainfall, wind and water erosion, low soil fertility, and poor soil management. Some of these constraints can be diminished by conservation tillage practices and improved nutrient management practices. This thesis characterizes the relations between rainfall and crop yields, and examines the effects of various tillage and nutrient management practices on erosion, crop yields and water and nutrient use efficiencies. The thesis is based on desk studies, long-term field experiments and model calculations.

The desk studies indicate that wind erosion in spring under conventional tillage removes on average between 50 and 1000 t ha^{-1} yr^{-1} of carbon (C) and between 5 and 90 kg ha^{-1} yr^{-1} of nitrogen (N) from the top soil of drylands in northern China. This high loss is related to the monsoonal climate with very dry winters and spring and wet summers with incidental very heavy rain showers. Yields of maize and wheat were highly related to the rainfall distribution. Results of the long-term field experiments indicated that the observed decline in crop yields over time were related to changes in total rainfall and its distribution over the growing season, but also to depletion of the soil potassium (K) reserve. Returning crop residues and manure to the soil was highly effective in restoring negative K and C balances. Reduced tillage, i.e. ploughing after harvest but not in spring before seeding, reduced wind erosion by 50-90%, and contributed to improved seedling emergence. The positive effect of reduced tillage on soil water availability to the crop was made stronger by use of crop residue, either incorporated or applied as surface mulch. Reduced tillage combined with improved nutrient management also increased water use efficiency (WUE) and nutrient use efficiency (NUE). The analysis of nutrient balances and soil fertility indices revealed that nutrient inputs in most treatments were far from balanced. It is concluded that the concepts of 'ideal soil fertility level' and 'response nutrient management' are applicable to the variable rainfall conditions of dry land areas. Simulations using the Century model were conducted to forecast the effects of management on soil organic carbon (SOC) dynamics.

Keywords: China, conservation tillage, crop residue, dryland farming, fertilizer, long-term, maize, manure, nutrient balance, nutrient dynamics, nutrient management, rainfall, soil fertility, soil organic carbon, wheat

Contents

Account

Chapters include published (Chapters 2A, 2B, 2C and 7) or submitted (Chapters 3, 4, 5, and 6) papers. :

Chapter 2A	Wang *et al.* (2006)*	*Pedosphere* (in press)
Chapter 2B	Wang *et al*. (2006)	*Soil & Tillage Research* (in press)
Chapter 2C	Wang *et al.* (2006)	*CATENA*, 66, 221-227
Chapter 3	Wang *et al.* (2006)	*Pedosphere* (to be submitted)
Chapter 4	Wang *et al.* (2006)	*Soil & Tillage Res.* (to be submitted)
Chapter 5	Wang *et al.* (2006)	*Nutrient Cycling in Agroecosystems*
Chapter 6	Wang *et al.* (2006)	*Nutrient Cycling in Agroecosystems*
Chapter 7	Wang *et al.* (2005)	*Pedosphere* 15(4), 473-483

* see chapter **References**

1 General introduction

1.1 Dryland farming

China has a large area of dryland in the North, which accounts for over 50% of the nation's total land area, covering 17 provinces. About 22% of the total population live here. Maize and wheat are the main cereals grown in the dryland area, accounting for 28% of the nation's cereal production. Twenty-seven percent of the nation's livestock is found here, contributing 17% to the national meat production. Thus, dryland farming is playing an important role in China's food supply, and yet, these regions are the least developed (Xin and Wang, 1999).

Crop production in the dryland areas of China is constrained by adverse weather (with low and highly variable rainfall), topography (hilly landscapes), erosion, and low fertility soils with low soil organic matter (SOM) and nutrient contents. There is a high risk for very low production levels or even crop failure, particularly under poor management.

Drylands are considered to be areas where average rainfall is less than the potential moisture losses through evaporation and transpiration. Worldwide, they occupy about 63 million km^2 or 47% of the surface of the earth (UNEP, 1992). They are subdivided in hyperarid (16%), arid (26%), semi-arid (37%), and dry subhumid (21%) areas (FAO, 2004). In China, regions receiving between 250-600 mm of precipitation annually are considered to be dryland regions with dryland-farming or rainfed-farming practices (Xin and Wang, 1999).

The sustainability of the dryland ecosystem and its agricultural production depends strongly on proper and effective land-use and management.

1.2 Land degradation

In China, just as in many other parts of our fragile world, there is a continuously growing population and rising food demand. In response to this demand, agricultural practices often are intensified. This in turn is leading to depletion of natural resources (water, land, and energy) and to degradation of the environment. It poses a serious threat to environmental quality, food safety, and human health. The northern part of China is an example of one of the many places in the world that face chronic water shortages and water pollution, arable land loss and soil degradation.

Desertification (or dryland degradation, Dregne (2002)) is a major and expanding global problem (UNEP, 1992). It refers to a collection of land degradation processes ("any process that reduces or destroys the biological productivity of dryland" (UNCOD, 1978)). Land degradation processes include: 1) Vegetation degradation, 2) Water erosion, 3) Wind erosion, 4) Salinization, 5) Soil compaction, and 6) Soil fertility decline. The causes of land degradation are related to various factors, including climatic variation and human activities, such as excessive cultivation, overgrazing and the removal of crop residues. There is a wide range of consequences of land degradation in drylands, such as: chemical degradation of the soil; loss of vegetation cover; loss of topsoil infiltration capacity; reduction in soil water storage; loss of soil organic matter, fertility and structure. The result is an increase in erosion potential, a loss of natural regeneration; and most important, a loss of soil resilience (FAO, 2004). The Intergovernmental Panel on Climate Change indicated that land degradation in semi-arid regions may experience increased climate stress (IPCC, 1990), by altering the surface energy balance due to the loss of plant cover, and modifying the scattering and absorption of solar radiation due to atmospheric dusts from deserts (Kassas, 1999).

China is one of the countries most seriously affected by desertification in the world. Land degradation affects around 2.6 million km^2 of a total of 3.3 million km^2 of drylands (excluding the extremely arid areas), accounting for over 27% of China's land territory (Dregne, 2002) or 79% of the dryland area. It threatens the productivity of agricultural soils in these areas, due to the loss of topsoil with valuable nutrients and organic matter (Song, 2004).

1.3 Soil conservation

The impacts of modern agricultural activities on the earth surface and environment have caused an increased and urgent demand for soil conservation measures. Conservation tillage generally refers to “methods of tillage that maintain a cover of crop residues on the soil surface and either reduce the amount of tilling (reduced tillage or minimal tillage) or eliminate it altogether (no-till)” (Acton and Gregorich, 1995). However, due to regional, technical, economical and institutional differences, the term “conservation tillage” is understood differently in different parts of the world. The US Conservation Technology Information Center developed the first widely accepted definition of conservation tillage as “any tillage and planting system that covers at least 30 percent of the soil surface with crop residue, after planting, in order to reduce soil erosion by water” (CTIC, 1999). Mannering and Fenster (1983) suggested that “a common characteristic of any conservation tillage is its potential to reduce soil and water loss relative to conventional tillage”. Conservation agriculture in Europe refers to “several practices, which permit the management of the soil for agrarian uses, altering its composition, structure and natural biodiversity as little as possible and defending it from degradation processes (such as soil erosion and compaction) and generally it includes any practice, which reduces, changes or eliminates soil tillage and avoids residue burning to maintain enough surface residue throughout the year” (ECAF, 1999).

Conservation tillage may be interpreted as “any system that promotes good crop yields while at the same time maintaining soil fertility, minimizing soil and nutrient loss, and saving energy/fuel inputs”. In Scandinavia, conservation tillage normally involves some form of reduced tillage, which covers alternatives ranging from systems that include thorough stubble cultivation in autumn followed by harrowing in spring, to direct drilling systems with no cultivation at all prior to sowing (Riley et al., 1994). Concerning the different climate conditions, soil types and cropping systems, conservation tillage does not necessarily mean less tillage; rather it needs to be suited to local agroecosystems in both space and time (Carter, 1994), where it serves to reduce soil and water loss as well as conserve natural resources relative to conventional tillage. A broad definition of conservation tillage given by Wittmus et al. (1973), namely "conservation tillage includes tillage systems that create as good an environment as possible for the growing crop and that optimize the conservation of soil and water resources, consistent with sound economic practices," seems to be well recognized and accepted.

During the 1970s reduced tillage or conservation tillage and mulch farming were proposed to solve soil erosion problems, and during the 1980s subsoiling and deep ploughing were proposed to alleviate soil compaction problems. Since the 1990s soil quality and environmental concerns, especially with conservation tillage practices, have received considerable attention. Computer modelling in the late twentieth century has also led to improved data analysis and understanding of this important issue (Lal, 2001b). Several studies also documented additional potential benefits associated with conservation tillage: 1) carbon sequestration (Uri et al., 1998) with smaller carbon emissions due to slow oxidation under low temperatures with no-till; 2) nutrient availability where adequate fertilizer inputs were generally more critical with conservation tillage systems (particularly no-till) than with conventional tillage systems and over the long term, requirements could decline as a result of accumulation and mineralization of organic matter (Rasmussen, 1999); and 3) yield response being equivalent or higher compared to those from conventional tillage practices (Lindwall and Anderson, 1981; Karunatilake et al., 2000; Guérif et al., 2001). Compared to conventional tillage practices, conservation tillage has shown to increase water storage, reduce water loss and wind erosion, to improve crop yield and water use efficiency, save energy and labour inputs.

Conservation tillage research in dryland regions of northern China started in the 1980's, via a large number of national and international research projects (Wang et al., 2006). The Chinese government has been actively involved in the demonstration and extension of conservation tillage practices from 2002 onwards, following the recognition of the environmental impacts of sand and dust storms, wind erosion, water erosion, and land degradation on dryland farming and economy of northern China (Zhang et al., 2004).

However, the current area under conservation tillage only accounts for 0.2% of the area worldwide (estimated between 50 and 60 Mha) where some form of no-till or conservation agriculture is applied (Bruinsma, 2003), and only about 0.1% of China's total arable land area. This area is far below what would be needed in view of the degradation of the land resource and soil quality in northern China. Therefore, strengthening research on conservation tillage and water, nutrient, organic carbon, and energy saving technologies is of great significance, with long-term benefits (Lal, 2001a, 2004a).

1.4 Problem definition

Crop production in dryland farming in China is influenced by a multitude of factors (Liu and Mou, 1988; Tao et al., 1993). Main constraints in crop production are: 1) Adverse weather, topography and water resource conditions; 2) Low fertility soils; and 3) Poor soil management. The increasing population results in a high demand for food, thus putting pressure on the land and forces farmers to increase land use intensity (Bi, 1995).

Figure 1.1 gives a summary of the problems and cause–effect relationships encountered with the conventional farming systems in northern China. It shows that the intensification of crop production under conventional soil management practices, including intensive soil cultivation, low or sub-optimal fertilizer and manure inputs, and crop residue removal and burning, has contributed to a range of negative environmental effects. Most important factors are soil, water and nutrient losses through wind and water erosion. This leads to degraded soils with low organic matter content and a fragile physical structure (Bi, 1995; Tang, 2004).

The awareness of the importance of conservation tillage practices for solving water scarcity and soil erosion in dryland farming has greatly increased over the last two decades. It is clear now that tillage and residue management can have major influences on water and nutrient availability, their use efficiencies, and on crop productivity. So far, various studies in China's dryland areas have shown the promise of reduced tillage in increasing water storage, reducing wind erosion, and saving energy and labour inputs, as compared to conventional tillage. Yields under no-till are usually equivalent to those from conventional methods in years with a common rainfall pattern, higher in dry years, but lower during wet years (Wang et al., 2006, Chapter 2A and 2B)

Despite the research efforts to explore the advantages of conservation tillage, and the dissemination efforts to promote conservation tillage, traditional cultivation with intensive ploughing and residue removal or burning still dominate in northern China. The slow acceptance and adoption of conservation tillage may in part be attributed to conceptual, scientific, and technological reasons and to the regional diversity in conditions. First, increasing food production through intensification of agricultural production has higher priority than environmental protection. Environmental protection is still low on the political agenda in China. Second, research on conservation tillage in China has only recently started; information on long-term site-specific tillage experiences in northern China is still sparse. Third, a low level of mechanization has limited the application of conservation tillage technology. Fourth, the highly diverse and small scale farming enterprises in China form a barrier to a smooth introduction.

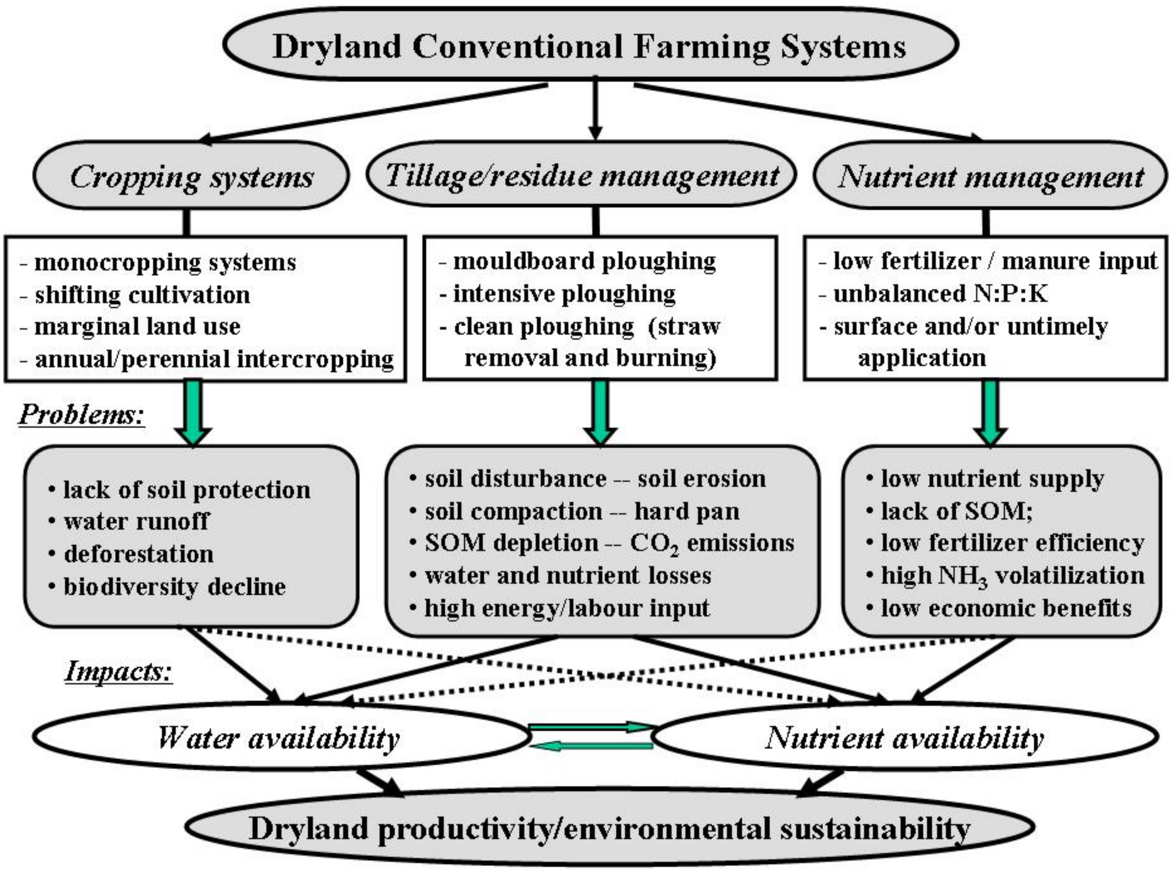

Fig. 1.1 Problems associated with conventional farming systems in northern China.

Because of the many interacting factors, crop yield is not always higher with conservation tillage than with conventional practices. For example, the often observed lower soil temperature when crop residues are left on the soil surface may negatively affect crop emergence. Further, even within a small region, tillage and residue management can be highly diverse. Lack of appropriate machinery for site-specific conservation tillage is than a constraint to the adoption of conservation tillage in practice. There is also competition with livestock in small crop-livestock systems, limiting the field application of crop residue. Use of crop residue for household fuel also competes with field application. Evidently, conservation tillage in the Chinese situation will have to be adjusted to site-specific conditions. Such adjustments may improve acceptance and may allow successful adoption of conservation tillage in practice.

In short, there is a lack of mechanistic understanding of site-specific success factors for implementation of conservation tillage in dryland areas in northern China. There is also a lack of knowledge about the possible side-effects of conservation tillage. What is needed? (1) A better understanding of possible interactions between conservation tillage and variations in weather on crop yield and environmental impact; (2) More knowledge of the long-term impacts of tillage practices on nutrient balances, soil fertility and crop production sustainability. With such information, better strategies of integrated conservation technologies can be drafted. This would provide stakeholders (scientists, extensionists and farmers) a scientifically sound framework and reference base for the determination, dissemination and implementation of tailor-made conservation tillage strategies. It would ease the difficult task of implementing these strategies in Chinese dryland farming systems with their small-scale mechanization and their wide variety of cropping systems.

1.5 Objectives of the study

The general objective of the study reported is as follows:
To improve the understanding of the interactions between conservation tillage and nutrient management in dryland farming systems in northern China;
Specific objectives are:

1. to provide an overview of the need for and perspectives of conservation tillage;
2. to assess the effects of rainfall on crop yields and water use, as function of tillage and nutrient management practices;
3. to assess the effects of combined applications of crop residue, cattle manure and fertilizer on crop yield, nutrient and water use efficiencies, nutrient balances and soil fertility indices, under conditions of reduced tillage;
4. to assess the effects of tillage, residue, and fertilization management on soil organic matter dynamics.

Figure 1.2 shows the conceptual model, in which the above research objectives are positioned.

1.6 Outline of the thesis

The study comprises literature reviews, long-term field experiments and simulation modelling. Literature was analysed, focussing on conservation tillage (in China and on a global scale), and on dust storm erosion in northern China. The field experiments involved various tillage and residue and nutrient management practices. Where needed, additional data were collected on weather, soil, and crops. A scenario analysis using the Century model aimed at forecasting the effects of management on soil organic carbon dynamics and potential carbon sequestration.

Field research was conducted at 4 sites in the dry semi-humid region of northern China (Fig. 1.3). Sites are Tunliu, Linfen and Shouyang counties of Shanxi province, and Luoyang of Henan province. These sites are located between 111°N and 113°N, and between 34°E and 38°E. A brief description of the research sites is given in Table 1.1.

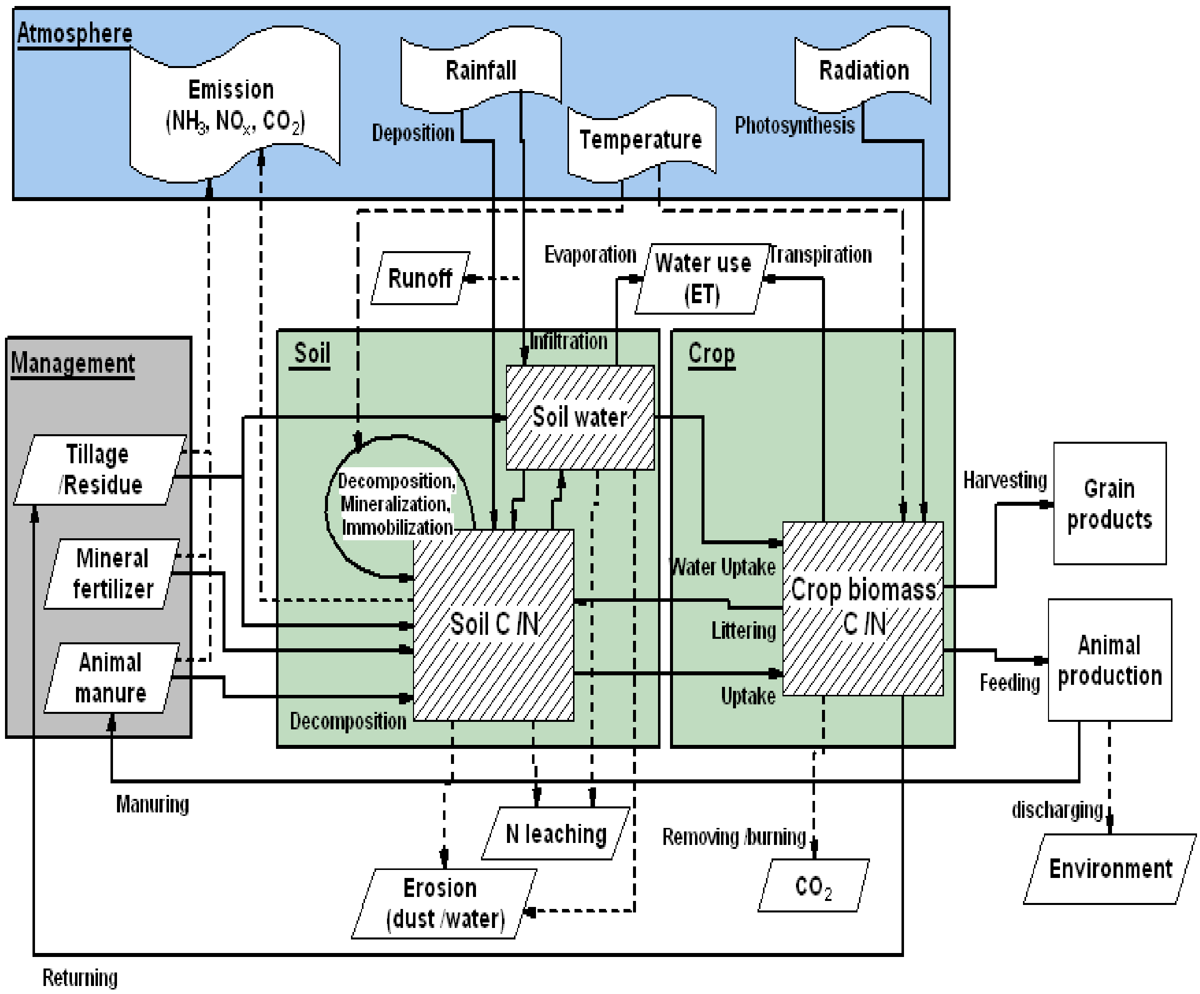

Fig. 1.2 Conceptual model of the weather, management, soil and crop factors influencing crop yields and the environment.

Fig. 1.3 Locations of the research areas in North China (★ – Research areas).

Table 1.1 Locations and conditions of the research sites.

Site**	Location	Elevation (m)	Soil type*	Annual rainfall (mm) Ave.	Max.	Min.	Annual ave. temperature (^{o}C)	Frost-free period (day)	Cropping system
Site 1: Tunliu, Shanxi	113°E, 36°N	945	Sandy clay loam (Calcic Luvisols)	550	917	312	9.4	160	Winter wheat; Spring Maize
Site 2: Linfen, Shanxi	111°E, 36°N	360-500	Sandy clay loam (Calcic Luvisols)	450	780	279	12.1	185	Winter wheat
Site 3: Shouyang, Shanxi	112°-113°E, 37°-38°N	1066-1159	Sandy loam (Calcaric-Fluvic Cambisols)	520	806	235	7.4	130	Spring maize
Site 4: Luoyang, Henan	113°E, 34.5°N	200-500	Sandy loam (Calcaric Cambisols)	570	1047	355	14.6	218	Winter wheat

* Source of soil classification: ISS-CAS, 2003; IUSS, 2006

** All sites were set up in the hilly loess areas located in the dry simi-humid region in northern China.

The thesis consists of the following chapters:
Chapter 1 gives a brief introduction to the thesis research.

Chapter 2 presents background information through literature reviews and desk studies to describing trends in soil conservation and conservation tillage practices on global, national and regional scales, with emphasis on dryland farming of northern China. Chapter 2 contains three papers: (1) “Potential effects of conservation tillage on sustainable land use -- a review of global long-term studies, (2) “Developments in conservation tillage in rainfed regions of northern China”, and, (3) “Dust storm erosion and its impact on soil carbon and nitrogen losses in northern China”,

Chapters 3, 4, 5 and 6 present results from the field studies. Chapter 3 analyses the effects of variation in rainfall on crop yields; Chapter 4 covers tillage and residue effects on rainfed wheat and maize production. Chapters 5 and 6 discuss nutrient dynamics in dryland maize cropping systems with emphasis on grain yield, and water and nutrient use efficiencies (Chapter 5); and on nutrient balances and soil fertility indices (Chapter 6).

Chapter 7 presents a scenario analysis of tillage, residue and fertilization management effects on soil organic carbon dynamics, using the Century model with input from the long-term field studies

Chapter 8 contains a general discussion and synthesis of the research findings. The consequences for future research and application of conservation tillage are discussed.

2 Literature reviews and problem analysis

2A Potential effect of conservation tillage on sustainable land use ---a review of global long-term studies

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Summary

Although understood differently in different parts of the world, conservation tillage usually includes leaving crop residues on the soil surface to reduce tillage. Through a global review of long-term conservation tillage research, this paper discusses the long-term effect of conservation tillage on sustainable land use, nutrient availability and crop yield response. Research has shown several potential benefits associated with conservation tillage, such as potential carbon sequestration, nutrient availability, and yield response. This research would provide a better perspective of the role of soil conservation tillage and hold promise in promoting application of practical technologies for dryland farming systems in China.

Keywords: *conservation tillage, no-till, reduced tillage, residue management*

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2A.1 Introduction

Conservation tillage generally refers to “methods of tillage that maintain a cover of crop residues on the soil surface and either reduce the amount of tilling (reduced tillage or minimal tillage) or eliminate it altogether (no-till)” (Acton and Gregorich, 1995). However, due to regional, technical, economical and institutional differences, the term “conservation tillage” is understood differently in various parts of the world. The US Conservation Technology Information Center developed the first widely accepted definition of conservation tillage as “any tillage and planting system that covers at least 30 percent of the soil surface with crop residue, after planting, in order to reduce soil erosion by water” (CTIC, 1999). Mannering and Fenster (1983) suggested that “a common characteristic of any conservation tillage is its potential to reduce soil and water loss relative to conventional tillage”. Conservation agriculture in Europe refers to “several practices, which permit the management of the soil for agrarian uses, altering its composition, structure and natural biodiversity as little as possible and defending it from degradation processes (such as soil erosion and compaction) and generally it includes any practice, which reduces, changes or eliminates soil tillage and avoids residue burning to maintain enough surface residue throughout the year” (ECAF, 1999).

Thus, conservation tillage may be interpreted as “any system that promotes good crop yields while at the same time maintaining soil fertility, minimizing soil and nutrient loss, and saving energy/fuel inputs”. For example, in Scandinavia conservation tillage normally involves some form of reduced tillage, which covers alternatives ranging from systems that include thorough stubble cultivation in autumn followed by harrowing in spring to direct drilling systems with no cultivation at all prior to sowing (Riley et al., 1994). Concerning the different climate conditions, soil types and cropping systems, conservation tillage does not necessarily mean less tillage; rather it needs to be suited to local agroecosystems in both space and time (Carter, 1994), where it serves to reduce soil and water loss as well as conserve natural resources relative to conventional tillage. A broad definition of conservation tillage given by Wittmus et al. (1973), namely “conservation tillage includes tillage systems that create as good an environment as possible for the growing crop and that optimize the conservation of soil and water resources, consistent with sound economic practices,” seems to be well recognized and accepted.

This research, then, is aimed at gaining an improved understanding of the long-term impacts of conservation tillage practices on sustainable land use, nutrient availability and yield response through a global review of long-term conservation tillage research. This would provide a better perception of the role of soil conservation tillage and may promote application of practical technologies for dryland farming systems in China.

2A.2 Background and benefits of conservation tillage

Recent conferences (Tullberg and Hoogmoed, 2003; Wang and Gao, 2004) have illustrated large interest in conservation tillage. Yet, long-term research on conservation tillage has been carried out for at least 30 years, especially in the semiarid and semi-humid regions with dryland farming, where it was concerned with crop production without supplemental irrigation. Several benefits from conservation tillage systems have been reported: 1) economical benefits (such as labor, energy, machinery cost, and time saved) (Uri et al., 1998; Uri, 2000; Stonehouse, 1997), 2) positive effects from erosion protection and soil and water conservation, and 3) increases in soil organic matter.

On the other hand, due to different weather and soil conditions, research has also reported low nutrient availability and inconsistent yield response with conservation tillage. For example, research in the United States for areas with low annual rainfall and on soils with low water holding capacity, such as light, well-drained silty loam soils, has suggested that the positive aspects of conservation tillage outweigh the negative aspects. On land with drought stress and serious erosion problems, the added water should increase yield potential in more southern latitudes. Meanwhile moldboard plowing or chiseling often has the highest rating on dark, poorly drained silty clay loams in northern latitudes, where the extra water may delay planting and reduce yield potential; and the lower temperature early in the growing season with surface residue systems could delay growth in the northern United States (Griffith et al., 1986).

A review from Riley et al. (1994) indicated that in Norway, some adverse effects of straw residues were found on poorly drained soils, and poor results were found after early sowing on silt soil with reduced tillage, probably due to waterlogging at germination. Better results were often observed in dry years than in wet years. Plowless tillage has been most successful in silty clay soils in Sweden. Long-term trials in Norway have had no negative trend in yields over a period of 15 years. Long-term research also documented several potential benefits associated with conservation tillage, such as potential carbon sequestration (Uri et al., 1998), potential nutrient availability (Rasmussen, 1999), and potential yield response (Guérif et al., 2001) from sustainable land use.

The introduction of mechanized plowing and other farming operations to meet the increase in food demand dates back to the early part of the twentieth century (Lal, 2001). During the 1950s the focus of soil tillage was on plowing, mechanization, and power requirements. The development of mechanized farming technology resulted in great increases in yields per unit of land and labor. This made it possible to expand production concurrent with the increase in food demand for an increasing global population. However, excessive plowing brought about undesirable effects, e.g. drastic soil disturbance exacerbated risks of wind and water soil erosion, and soil compaction that led to the development of hard pans and poor soil tilth. In addition, the combination of inversive soil tilling and more intensive cropping methods increased the rate of soil degradation, e.g., deterioration of soil structure, accelerated erosion, depletion of soil organic matter and fertility, and disrupted cycles of water, organic carbon and plant nutrients (Lal, 1993). Soil degradation in turn was found to be detrimental to long-term soil productivity (Larson et al., 1983; Norwood et al., 1990). Therefore, during the 1970s reduced tillage or conservation tillage and mulch farming were proposed to solve soil erosion problems, and during the 1980s subsoiling and deep plowing were proposed to alleviate soil compaction problems. Since the 1990s soil quality and environmental concerns, especially with conservation tillage practices, have received considerable attention. Computer modeling in the late twentieth century has also led to improved data analysis and understanding of this important issue (Lal, 2001).

The earliest adoption of conservation tillage occurred in Canada. More than 60 years ago, Canadian scientists, alerted to the dangers of wind erosion during the “dirty thirties” (the Dust Bowl of the 1930s), began researching methods to control soil erosion (Toogood, 1989). Long-term studies demonstrated economic benefits from conservation tillage systems, including reduced inputs of labor, energy, machinery, and time (Uri et al., 1998; Uri, 2000; Stonehouse, 1997), along with positive effects from reduced soil erosion (Riley et al., 1994), soil and water conservation (Hussain et al., 1999), and increased soil organic matter (Rasmussen, 1999; Williams et al., 2005). Studies also documented several potential benefits associated with conservation tillage: 1) potential carbon sequestration (Uri et al., 1998) with smaller carbon emissions due to slow oxidation under low temperatures with no-till; 2) potential nutrient availability where adequate fertilizer inputs were generally more critical with conservation tillage systems (particularly no-till) than with conventional tillage systems and over the long term, requirements could decline as a result of accumulation and mineralization of organic matter (Rasmussen, 1999); and 3) potential yield response where even though the crop yield with no-till was not usually reduced (Guérif et al., 2001), yields could be equivalent or higher compared to those from conventional tillage practices (Lindwall and Anderson, 1981; Karunatilake et al., 2000). Nevertheless, yields depended on site-specific conditions, such as climate zones, soil types, crop species, cropping systems, length of time, water conditions and fertilizer application.

2A.3 Site-specific limitations of conservation tillage

2A.3.1 Weather conditions

In semi-arid regions under rainfed agricultural systems, water is the most limiting factor in crop production. Also crop yields with different tillage systems vary from year to year due to fluctuations in weather. In terms of yields, the best tillage system is often a function of the weather experienced in that year (Lampurlanés et al., 2002). Weather conditions in the growing season also appear to play a part in the success of no-till systems. A review by Riley et al. (1994) indicated that in Norway, better results were often observed in dry years than in wet years. Eckert (1984) reported no-till maize yielded more in drier than in normal years, whereas in the moderately well-drained soils of Ohio the yields with moldboard plow were higher in wetter rather than in normal years. Hussain et al. (1999) also reported that no-till yields were 5%--

20% lower than with the moldboard plough system in wet years, but were 10%--100% higher in relatively dry years. A report that summarized several years of Agriculture and Agri-Food Canada research in Saskatchewan, Canada, indicated 5%--25% yield advantages in no-tillage systems at Melfort, 0--18.5% yield advantages at Indian Head, and an 11.4% advantage for wheat versus a 5.7% yield disadvantage for oilseeds at Scott (GCGS, 1993).

In another case Lal and Ahmadi (2000) studied the effects of three tillage methods on maize yield in silt loam soil for 11 years in central Ohio, USA, and found that there were no consistent trends in grain yields from year to year. However, chiseling treatment out-yielded the no-till and moldboard tillage treatments. Elsewhere, a study in a fallow-wheat rain-fed cropping system in Australia reported that the differences in yields among three tillage methods were not consistent from year to year but that a pattern was evident. In years of low rain, no tillage had a yield advantage over tillage methods, fully tilled fallow and blade plough (Cantero-Martinez et al., 1995). The advantage of chemical fallow in years of low rainfall and yield potential was shown to result from greater water conservation, while the advantage of fully tilled fallow in years of greater yield potential can be attributed to better N supply.

2A.3.2 Soil types

Due to regional differences in climate conditions and soils, there is no universal tillage or cropping system that is best for all situations. Nevertheless, changes in soil structure could affect the relative success of conservation tillage (Karunatilake *et al.*, 2000). Studies in Canadian brown and dark brown soil zones showed that the effects of tillage systems on yields of barley, winter wheat and spring wheat varied from year to year but were, on average, equal (Carefoot *et al.*, 1990a, 1990b; Tessier *et al.*, 1990; Brandt, 1992; Larney and Lindwall, 1994). In the black and gray soil zones of Western Canada, yield increases with no tillage over conventional tillage varied from 0 to 23% for barley, spring and winter wheat, flax, canola and field pea (Stobbe *et al.*, 1970; Lafond *et al.*, 1996; Arshad *et al.*, 1994; Borstlap and Entz, 1994). In the North Central and Northeastern USA weather and soil type strongly affected the relative success of reduced and no-till methods with fine-textured and poorly drained soils generally posing the greatest challenge to their adoption (Johnson and Lowery, 1985; Griffith *et al.*, 1986; Lal *et al.*, 1989; Cox *et al.*, 1990). In general, it has been determined that well-drained soils, light to medium in texture with a low humus content, respond best to conservation tillage (Butorac, 1994). The most obvious advantage of reduced tillage from an environmental viewpoint is its role in minimizing the risk of erosion (Riley *et al.*, 1994). Further expansion of conservation tillage on highly erodible land will result in a smaller impact on the environment and an increase in social benefits; nevertheless, the expected gains are likely to be modest (Uri *et al.*, 1998).

2A.4 Impact of Length of time in conservation tillage

2A.4.1 Potential yield response

One Rice and Smith (1984) reported that maize yields under no-till were lower than those of conventional tillage during the three early years of their study, but during the last five years of study the no-till system out-yielded the moldboard plough system. The authors concluded that the low yields during the early years of the experiment could be due to lower soil organic carbon, nitrogen mineralization and higher immobilization of fertilizer. Meanwhile, Linden et al. (2000) reported no significant effects on grain yield due to tillage treatments in 9 out of 13 years. However, this long-term study indicated a gradual decrease in yield over time with continuous use of no-till. In 8 out of 13 years these differences were due to residue management. In intermediate level dry years the residue-returned treatments contributed about 1 Mg ha-1 greater yields, whereas in excessively dry or long-term-average years, residues resulted in little yield difference among treatments. Rice et al. (1986) and Kapusta et al. (1996) with no-till and conventional tillage also reported no differences in maize yield over time.

There are still risks with conservation tillage, including biological risks (increased pest and disease problems), physical risks (changed cycling of nitrogen and increased nutrient requirements due to nutrient immobilization under cold soil temperatures) and chemical risks (increased herbicide use) (Baker et al., 1996). However, positive soil promoting factors would be expected to increase over time as a result of converting from tillage to no-tillage. On the likely short- and long-term trends with no-tillage, Choudhary and Baker (1994) predicted that despite potential negative results in the first few years of no-till, potential benefits of the reduced fertilizer requirements and pest protection as well as an increased stable crop yield would be realized with longer-term no-till. Nonetheless, during these early years there would be significant benefits from the improved earthworm numbers and soil structure, as well as the reduced total input costs (labour and tractor hours per year) associated with no-tillage.

2A.4.2 Potential carbon sequestration

Soil C loss and tillage-induced CO_2 emissions associated with intensity tillage affect not only productive capacity but also global environmental quality. Thus, soil C sequestration through conservation tillage methods is considered one of the most cost effective ways to slow processes of global warming (Reicosky, 2001a; 2001b). Conservation tillage may also slow global warming through reduced production of fossil fuel emissions and less fossil fuel consumption (Derpsch, 2001).

Depending on planting frequency, increases in soil C may take 5-10 years to come into effect. In a study at Swift Current, SK, Campbell et al. (1995) reported that between 1986 and 1994 organic C concentration under direct seeded continuous wheat changed from 1.75% to 1.83%. Over the same time period for a direct seeded/chemical fallow wheat-fallow rotation, the change was from 1.63% to 1.60%. In another study, after 11 years of direct seeding of continuous wheat on a fine sandy loam soil in southwestern Saskatchewan, organic carbon in the 0-7.5 cm depth increased 21%, but there was no change in organic carbon in the 7.5-15 cm depth. Meanwhile, at Lethbridge, Alberta, 16 years of conventionally tilled fallow resulted in a decrease of 2.2 Mg ha^{-1} soil C compared to the least intensive conventional tillage treatment or the no-tillage treatment (Larney et al., 1997). Nevertheless, in a continuous spring wheat study, 8 years of no-tillage compared to conventional tillage prior to planting, increased total organic C 2 Mg ha^{-1}, and increased the mineralizable and light fractions of C and N 15%-27%. In another example in southwestern Saskatchewan, over a 12-year period, a no-till continuous wheat system gained approximately 1.5 Mg ha-1 more C in the 0-15 cm soil depth than did a continuous wheat system under conventional tillage. Additionally, at the end of 6 years of direct drilling in Denmark, Rasmussen (1988) found that after direct drilling organic C increased significantly (by 7.9 g kg^{-1}) in the upper 0-2 cm soil layer, but in the 2-10 and 10-20 cm depths the increases were not significant. Thus, the potential gain in soil organic matter varied among sites depending on soil and environmental variables, tillage and residue practices, initial organic C, rate of C input, source of organic material, time of C application, fertilizer use, and cropping systems.

2A.5 Potential nutrient availability of conservation tillage

2A.5.1 Fertilizer N

Due to changes in the soil physical, chemical, and biological environment, the rates of N transformation in conservation tillage systems differ from those in conventional tillage systems. Under conservation tillage the soil is wetter (Lafond et al., 1992) and more compact in the top 10 cm (Grant and Lafond, 1993) than under conventional tillage systems with soils warming up more slowly in spring (Malhi and O'Sullivan, 1990). As temperatures in fall and winter are apt to be warmer under conservation tillage systems, this could lead to higher N losses after harvest. Conservation tillage systems leave more organic matter (Hendrix et al., 1986), and have a higher microbial biomass, particularly more denitrifiers, facultative anaerobes and aerobic microorganisms in the surface (0-7.5 cm) of soils, but have fewer nitrifiers and aerobic conditions. The net result is potentially greater rates of immobilization and denitrification of applied N, but slower rates of mineralization and nitrification with more organic matter accumulation and a less oxidative biochemical environment. This is reflected in lower fertilizer N availability to crops under conservation tillage as compared with conventional tillage (Doran, 1980), at least in the initial years of reduced tillage.

Since usually more nitrogen would be applied to compensate for any sub-optimal physical or biological conditions resulting from no-till systems (Riley et al., 1994), optimum fertilization is more critical with no-till than with conventional tillage systems. In drier regions, the additional stored water with conservation tillage increases the yield potential, requiring a greater supply of available N. This may, in part, explain the increased need for N in the early years of some conservation tillage systems (Schoenau and Campbell, 1996). The excess crop residue on the surface leads to an increased nitrogen requirement for soil microorganisms to decompose the straw (McGill et al., 1981; Campbell et al., 1986). No-till systems may stabilize or increase soil organic matter content as a consequence of reduced oxidation (slower mineralization) and increased immobilization. This may also partly explain the observed lower recovery of added fertilizer N in early no-till systems (Legg et al., 1979).

Greater immobilization in reduced and no-till systems can enhance in the long term the conservation of soil and fertilizer N. Higher soil test N values were observed in the no-till treatment with a long-term comparison of soil test N in the top 60 cm for wheat on fallow grown on a Hatton fine sandy loam in southwestern Saskatchewan (Schoenau and Campbell, 1996). Additionally, fertilizer requirements may even be expected to decline over time as a result of organic matter accumulation (Riley et al., 1994) and reduced erosion losses (Schoenau and Campbell, 1996). Precise placement of N-fertilizer in a no-till system with side-banding can reduce the immobilization effects as the no-till drill separates the fertilizer and residue (Malhi and Nyborg, 1992).

2A.5.2 Residue-nutrient availability

When residues are surface applied or incorporated into the soil, the impacts of crop residues on nutrient availability differ. Rennie and Heimo (1984) reported that incorporation of straw into soil led to significantly lower barley yields than when the straw was left on the soil surface. Furthermore, surface placement of the straw reduced N immobilization as compared to straw incorporated into the soil. Because of greater fluctuations in surface temperature and moisture as well as reduced availability of nutrients to microbes (Douglas et al., 1980; Schomberg et al., 1994), soil-incorporated residues tend to decompose faster than surface residues and have a higher potential for N immobilization (Brown and Dickey, 1970). In addition, Schnürer et al. (1985) demonstrated that residue added to soil with manure or nitrogen fertilizer led to residue decomposition rates that were two times greater than when no amendments were added. Rasmussen et al. (1997) found that standing straw residue had a strong adverse effect on wheat yield as well, decreasing yield of winter wheat by 13% compared with chopped straw. Additionally, where the surface temperature during the spring maize seedling period was reduced 2-6 °C, lower yield has been reported with stubble surface application as compared with treatments where stubble was removed or incorporated (Cai and Wang, 2002).

2A.6 Limitations to and needs for adoption of conservation tillage in northern China

Although soil tillage systems have been greatly improved in northern China since the 1970s, traditional intensive cultivation is still dominant in the area. Most farmers still use intensive plowing instead of no-till or reduced tillage practices, and clean fields by burning or removing straw instead of returning straw to the soil. The slow acceptance and adoption of conservation tillage practices may be attributed to some reasons that are conceptual, scientific, and technological, as well as associated with regional conditions. First, as farming intensifies, the depletion of soil fertility has increased environmental concerns and emphasized the need for soil conservation practices. However, increasing food production has always been a challenge for feeding China’s population. Second, although greater emphasis has been placed on conservation tillage in China, information on long-term site-specific tillage experiences in northern China is still sparse. Third, low mechanization has limited the application of conservation tillage technology.

As discussed previously, because of many factors including site-specific conditions such as climate, soil types, cropping systems, length of time, water and fertilizer management, as well as the local resource and economic situation, crop yield is not always higher with conservation tillage as compared to conventional practices. Even in the same region tillage and residue management cannot be universal. Constraints to adoption of conservation include lack of appropriate machinery for site-specific conservation tillage systems, which means more hand work is needed; competition with livestock (some for fuel) in small crop-livestock systems, in which crop residue for land application is limited; and temperature impacts on crop emergence caused by residue surface cover, meaning residue cover is not always a successful practice in a temperature-limited situation.

Therefore, to develop a sustained agricultural industry in China that reduces the risk of yield failure and that is integrated, applicable and advanced, technologies are needed to ensure successful acceptance and adoption of conservation methods. These include the need for better understanding of soil conservation and environmental protection, the need for better knowledge of the long-term impact of site-specific tillage practices, and the need to develop appropriate practical technologies while addressing financial constraints. Among these, elucidating scientific knowledge and developing practical technologies to let people know why and how to adopt conservation agriculture technologies that comply with local sustainable land use, meet environmental quality, and allow for food production needs, are the most critical elements.

2B Developments in conservation tillage in rainfed regions of northern China

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Summary

Dryland regions in northern China account for over 50% of the nation's total area, where farming development is constrained by adverse weather, topography and water resource conditions, low fertility soils, and poor soil management. Conservation tillage research and application in dryland regions of northern China has been developed since the 1970s. Demonstration and extension of conservation tillage practices is actively stimulated by the Chinese government since 2002, following the recognition of the increased rate of degradation of the environment due to erosion and water shortage in North China. This paper reviews the research conducted on conservation tillage in dryland regions of northern China, and discusses the problems faced with the introduction and application of conservation tillage practices.

Most of the studies reported have shown positive results of soil and water conservation tillage practices. These practices generally involve a reduction in the number and intensity of operations compared to conventional tillage, with direct sowing or no-till as the strongest reduction. Crop yields and water use efficiency have increased (with up to 35%) following the implementation of reduced tillage practices. Under no-till, crop yields are equivalent to or higher than those from conventional tillage methods, especially in dry years. However, during wet years yields tend to be lower (10-15%) with no-till. Other benefits are an increased fallow water storage and reductions in water losses by evaporation. In order to fully exploit the advantages of conservation tillage, systems have to be adapted to regional characteristics. Farmers' adoption of conservation tillage is still limited.

Keywords: *conservation tillage; residue management; dryland farming; China; technology adoption*

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2B.1 Introduction

This research, then, is aimed at gaining an improved understanding of the long-term impacts of conservation tillage practices on sustainable land use, nutrient availability and yield response through a global review of long-term conservation tillage research. This would provide a better perception of the role of soil conservation tillage and may promote application of practical technologies for dryland farming systems in China. Regions receiving between 250-600 mm of precipitation annually are considered to be dryland regions where dryland or rainfed-farming (crop production in low-rainfall areas without irrigation) is practiced (Xin and Wang, 1999). China has a large region of dryland in the North, which accounts for about 56% of the nation's total land area (Xin and Wang, 1999). Dryland farming in northern China is dominated by mono-cropping systems with mainly maize (Zea mays L.) and wheat (Triticum aestivum). Crop production in this dryland region is constrained by adverse weather, topography and water resource conditions (deep groundwater, very limited access to surface water), and low fertility soils under poor management. Conventional soil management practices include intensive soil cultivation, low fertilizer and manure inputs, and crop residue removal and burning. These practices have contributed to an exacerbation of soil, water and nutrient losses, and to degraded soils with low organic matter content and a fragile physical structure (Bi, 1995; Tang, 2004). This in turn has led to low crop yields and a low water and fertilizer use efficiency. The depletion of soil fertility and the decline in agricultural productivity in northern China have led scientists and policy makers to emphasize the need for the implementation of farming practices that contribute to the conservation of soil and water, with tillage as an important component of these practices (Wang, 1994; Lal, 2002).

The Chinese government is actively involved in the demonstration and extension of conservation tillage practices since 2002 (Zhang et al., 2004). This involvement was triggered by reports about the devastating eco-environmental degradation: topsoil loss, land degradation, air pollution, damage to trees, vegetation, buildings, transportation structures and waterways, and the deterioration of the living environment of human beings and livestock. This degradation was also shown by an increased frequency and intensity of dust storms, wind and water erosion and the loss of fertile top soil in northern China (Yang et al., 2001; Wang et al., 2004, 2006; Guo, 2004). The Chinese Ministry of Agriculture has formulated a plan for promoting a widespread application of conservation tillage throughout dryland regions of northern China within 7-10 years. Since 2002 about 60 demonstration counties within 13 provinces (municipalities and autonomous regions) of northern China, including Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Shandong, Henan, Shaanxi, Gansu, Ningxia, Qinghai, and Xinjiang were established (Rural Pastoral Area Mechanization, 2003). Demonstration areas covered 0.13 million ha in 2003 and are expected to reach 10 million ha in 2015. Notwithstanding these efforts, the present area under conservation tillage in China only accounts for 0.2% of the area worldwide where some form of no-till or conservation agriculture is applied (Bruinsma, 2003).

This paper reviews the research on conservation tillage in northern China and discusses the problems associated with the introduction and application of conservation tillage practices and their regional adaptation.

2B.2 Site-specific limitations of conservation tillage

2B.2.1 Climate

Figure 2B.1 shows the dryland zones in northern China according to annual rainfall distribution pattern, based on INASR (1986). Five zones have been distinguished, i.e., 1) arid (<250 mm); 2) arid semi-arid (250-350 mm); 3) semi-arid (350-500 mm); 4) dry semi-humid (500-600 mm); and 5) semi-humid (600-700 mm). Table 2B.1 describes the characteristics and the dryland farming practices for each of these zones. The annual evapotranspiration ranges from 750 to 1080 mm, and the annual water deficit ranges from 40 to 740 mm (Table 2B.2).

2B.2.2 Soil characteristics

The most important soil types are Desert soils and Aeolian soils in North-West, Loessial soils in the Loess Plateau, Dark-brown earths and Black soils in the North-East, and Cinnamon soils and Fluvo-aquic soils in the North China Plain region (soil classification based on ISS-CAS, 2003). The soils are neutral or alkaline with pH values ranging from 7.0 to 8.5, and with Ca and Mg as dominant exchangeable cations. On average, soil organic matter content is low (around 6-12 g kg^{-1}), due to a long farming history with intensive soil cultivation. Originally, soils are rich in K, but low in P. The range of available nutrients is 40-100 mg N kg^{-1}, 3-10 mg P kg^{-1}, and 70-150 mg K kg^{-1} (Bi, 1995). The total N content ranges from 0.6 to 1.0 g kg^{-1} and total P from 0.4 to 1.0 g kg^{-1}.

Severe water and wind erosion have caused the formation of a hilly landscape with a complicated topography. This is especially true in the northern regions, where the soils are mainly loess or loess-derived with steep slopes and with severe fertility limitations. Problems are prominent on land with eroded soil, land susceptible to drought, land with shallow soils, land with saline/sodic limitation, and desertified land. They account for approximately 58% up to 95% of the national problem soils (Fig. 2B.2).

2B.2.3 Crops

Rainfed crops grown in northern China include winter and spring wheat, maize, naked oat (Avena nuda), barley (Hordeum vulgare), potato (Solanum tuberosum), sorghum (Sorghum spp.), millet (Panicum miliaceum), soybean (Glycine max), pea (Pisum sativum), buckwheat (Fagopyrum esculentum), sunflower (Helianthus annuus), flax (Linum usitatissimum), rape (Brassica napus), cotton (Gossypium herbaceum), and tobacco (Nicotinia tabacum) (Wang, 1994). An indication of the evolution over time of the yields of dryland cereals is given in Figure 2B.3. Table 2B.3

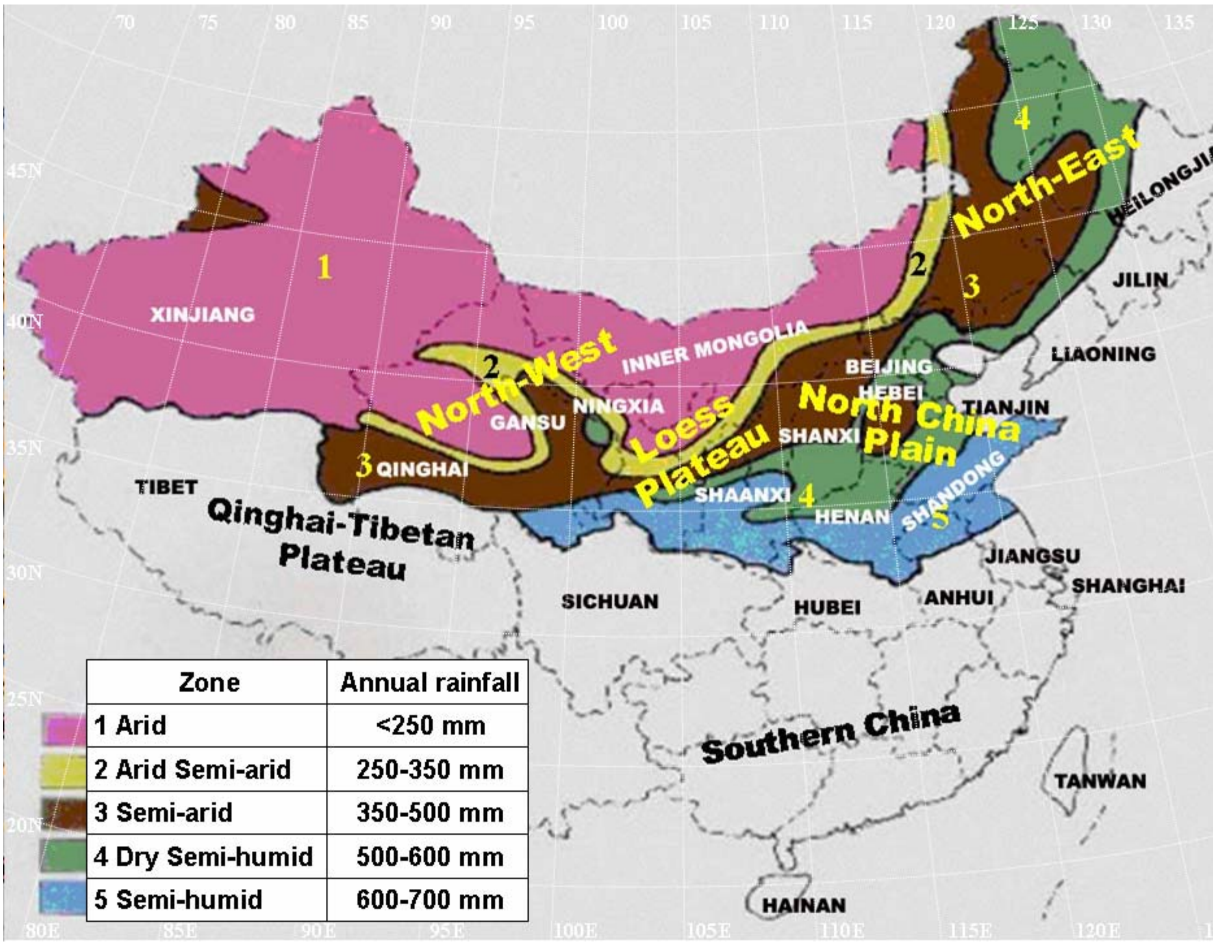

Fig. 2B.1 Map of the climatic and agricultural zones in North China (modified from Xin and Wang, 1999).

shows the area and the crop production volumes in three climatic zones. The percentage of arable land under irrigation in the different zones ranges from 16 to 39.

Table 2B.4 describes the most common cropping systems in the dryland farming regions. The regional distribution of these systems is given in Table 2B.1. Some shifting cultivation is practiced in hilly areas in some areas of North-West and North-East regions (Li, 2004).

2B.2.4 Tillage and crop residue management practices

Traditional tillage in dry farming areas of northern China involves mouldboard ploughing (animal drawn or motorized) to a depth of 16-18 cm, followed by a sequence of harrowing, smoothing, rolling and hoeing. These operations are done with all crop residues removed, being used as fodder for animals or as fuel (Liu and Mou, 1988; Gao et al., 1991; Wang, 1994). Burning crop residue has increased during the last decades (Wang et al., 1999).

Table 2B.1 Dryland farming zones and their regional characteristics of northern China (based on INASR, 1986; Xin and Zhang, 1987)

Climatic Zonification	Main agricultural regions (provinces covered)	Main soil types[1]	Rainfall / dryness[2]	Temperature regime[3]	Cropping / livestock system[4]
Arid ***(Zone 1)***	***North-West desert region*** (Xingjiang, Inner Mongolian, part of Gansu, Ningxia, Qinghai)	Desert soils & Aeolian soils	<250 mm/yr; dryness >3.5;	0~10℃ mean/yr; sum 2000-4500℃; 90-240 frost-free days	- animal husbandry; - grazing; - irrigated wheat and cotton; /- 1 crop/yr
Arid semi-arid ***(Zone 2)***	***North-West windy-sandy region*** (eastern part of Inner Mongolian, Margin of desert in Gansu, Ningxia, and western part of NE)	Aeolian soils & Loessial soils	250~350 mm/yr; dryness 3.0~3.5;	1~8℃ mean/yr; sum 2400-3800℃; 100-160 frost-free days	- animal husbandry; - grazing; - rainfed spring wheat, millet, naked oats, potato; /- 1 crop/yr
Semi-arid ***(Zone 3)***	***Loess Plateau hilly-gully region*** (most parts of Shaanxi, Shanxi, Gansu, Ningxia, Qinghai)	Loessial soils	350~500 mm/yr; dryness 1.6~3.0;	4~10℃ mean/yr; sum 1500-4900℃; 100-200 frost-free days	- extensive farming /-marginal land use; - rainfed spring wheat, spring maize, millet, sorghum, potato; /- 1 crop/yr
Dry semi-humid ***(Zone 4)***	***North-East cold & North China Plain region*** (Jilin, Heilongjiang, Liaoning; Hebei, Henan, Beijing, Tianjin)	Dark-brown earths & Black soils; Cinnamon soils & Fluvo-aquic soils	500~600 mm/yr; dryness 1.3~1.6;	-5~9℃(NE) /8~15℃; sum 3000-5200℃; 100-240 frost-free days	- intensive tillage; - rainfed winter wheat and spring maize; some irrigated; - 1 crop/yr; 3 crop/2 yrs; 2 crop/yr
Semi-humid ***(Zone 5)***	***North China Plain region*** (Shandong, part of Henan and Shaanxi)	Cinnamon soils & Fluvo-aquic soils	600~700 mm/yr; dryness 1.0~1.3;	10~14℃ mean/yr; sum 2800-5200℃; 120-210 frost-free days	- intensive farming - straw burning; - irrigated winter wheat /summer maize; - 3 crop/2 yrs; 2 crop/yr

[1] Soil classification based on ISS-CAS (2003)
[2] Dryness: ratio of annual evaporation to annual precipitation. Evaporation is calculated using open pan data.

Table 2B.2 Annual potential evapotranspiration (ET_0) and water deficit in dryland regions of northern China (1951-1987) (modified from Leng and Han, 1996).

City, Province	Climatic zone	ET_0 (mm yr^{-1})	Water deficit (mm yr^{-1})
Urumqui, Xinjiang	**1**	970	-593
Yinchuan, Ningxia	**1**	1079	-742
Lanzhou, Gansu	**1**	908	-540
Yuzhong, Gansu	**2**	986	-562
Haiyuan, Ningxia	**2**	1156	-753
Huhehaote, Inner Mongolia	**3**	870	-435
Xining, Qinhai	**3**	874	-527
Shijiazhuang, Hebei	**3**	905	-355
Datong, Shanxi	**3**	877	-493
Taiyuan, Shanxi	**3**	852	-414
Xian, Shaanxi	**4**	794	-233
Beijing	**4**	927	-283
Changchun, Jilin	**4**	830	-237
Harbin, Heilongjiang	**4**	791	-273
Shenyang, Liaoning	**5**	749	-39

ET_0 is estimated using FAO modified Penman equation by Frère and Popov (1979)
Data for climatic zone 2 are based on Yan et al. (2002)

Tractors have steadily replaced draft animals since 1970. As an example, a survey in the village Zongai (with 400 ha farmland) of Shouyang in Shanxi province (the dry semi-humid zone) showed that the number of tractors, increased from 1 tractor in 1973, to 4 tractors in 1983, and 28 tractors in 1993. Data from all of China show a 75-fold increase in tractor numbers from 1970 to 2003 (Li, 2005).

Intensive ploughing has contributed to increasing risks of soil erosion by wind and water, but also to soil compaction and the formation of a hard pan in the subsoil layer (Cai and Wang, 2002; Gao et al., 1991). It has also resulted in soil organic matter depletion, reducing soil structural stability, soil fertility, and soil water retention (Cai et al., 1994, 1995). Traditional farming methods require high inputs of energy and labour that are about 60-70% higher than for reduced tillage practices (Wang et al., 2003b).

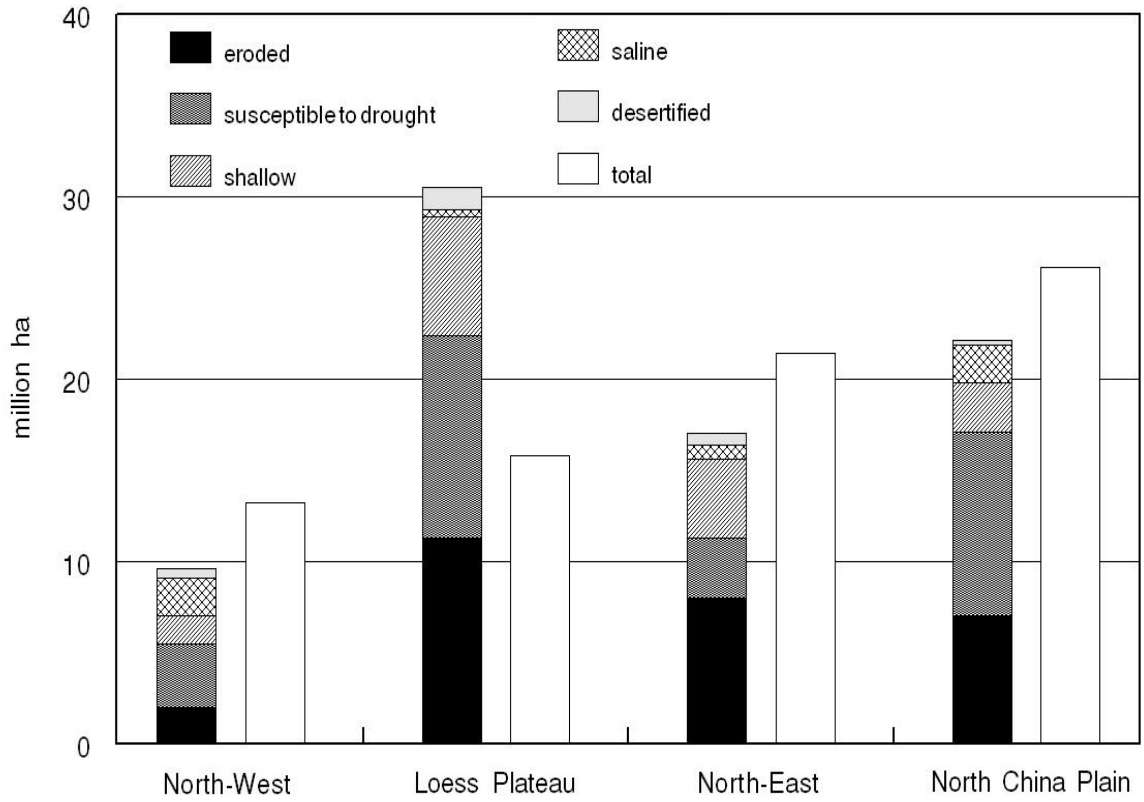

Fig. 2B.2 Main problem soils in the dryland regions of North China, as modified and recalculated from Bi, 1995. Soils may be associated with more than one problem.

Table 2B.3 Crop production in dryland farming zones of northern China (modified and recalculated from Tao et al., 1993; Xin and Wang, 1999).

Climatic zone (ref. Table 1)	Population (million)	Total area (million ha)	Arable land (million ha)	% irrigated	Total cereals (million ton)	Yield (1000 kg ha^{-1})
2	6.5	13.1	1.8	16.3	1.9	1.1
3	93.0	74.6	15.8	29.7	51.1	3.2
4	130.0	35.0	15.3	38.7	65.8	4.3
Total China	1184.7		94.9	52.0	466.6	4.9
% of total China	19.4		34.7		25.5	

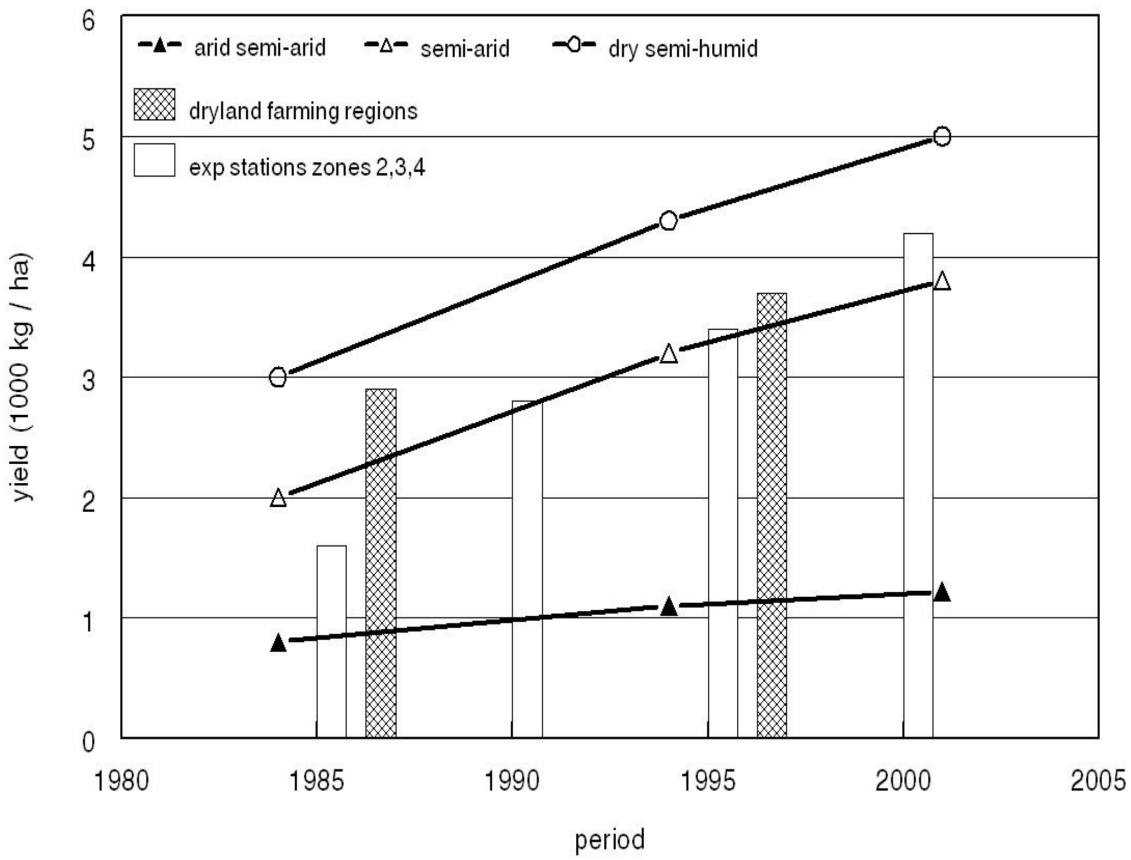

Fig. 2B.3 Trends in cereal yields in the dryland zones of North China. Data based on Wang (1994), and Xin et al. (2002)

Table 2B.4 Cropping systems of the dryland farming regions.

cropping system	crops*	seasonal distribution
single	wheat maize *millet* *sorghum* *potato*	Wheat will be grown as winter wheat (sown in autumn), temperature permitting. Otherwise wheat is grown as summer crop (sown in spring), as are all other crops listed. Maize is preferred as summer crop (sown in spring), millet and sorghum are sown when water availability is too low.
three crops in two years	maize (s) sorghum (s) millet (s) sweet potato (s) wheat (w)	One of the (s) crops sown early spring of year 1, followed by wheat sown in autumn of year 1, followed by (s) again in year 2, but now sown late spring – early summer. Autumn and winter of year 2 is fallow.
two crops per year	wheat maize	Wheat is grown in winter (autumn sown) followed by maize grown in summer (spring sown)

* Annual and perennial intercropping is practiced locally: maize with legumes/potato, cereals with forage grass/legumes, and relay intercropping of cereals with potato/forage grass.

2B.2.5 Nutrient management

In China, fertilizer is the most costly input in crop production. In 1990/91, mean fertilizer cost in China accounted 25% of the total expenses for agricultural production (cost of input material plus labour), and 50% of total cost for input materials (cost for seed, fertilizer, pesticide, machinery, irrigation) (Lin et al., 1999). Although fertilizer use has greatly increased, most of it is applied on fertile soils in the lowland and the developed areas. Little or no fertilizer is applied in much of the land in hilly areas with shifting cultivation practices, especially in the poor areas of the Loess Plateau region. The use of fertilizer in dry farming areas of northern China is less than half of the mean national fertilizer use (which was 235 kg ha^{-1} in 1998 (FAO, 1999)). The average fertilizer input in 1995 (in kg ha^{-1}) was 169 in zone 1 (Table 2B.1), 28 in zone 2, 124 in zone 3, 223 in zone 4, and 238 in zone 5 (Xin et al., 2002). The survey in Zongai village provides an indication of the trend in fertilizer use in the dry semi-humid zone of northern China during the period 1963 to 1999. Before the 1970s farmyard manure was the main source of nutrients applied. Fertilizer use increased until the 1990s, and has been maintained since at levels of approximately 130 kg N and 25 kg P per hectare (Wang et al., 1999), with a ratio of N:P 1:0.2. This ratio of N to P is higher than the recommended ratio of 1:0.3 for dryland. Use of animal manure did not increase during the last years, because of the slow development of animal production. The average amount of animal manure applied was 4875 kg ha^{-1} (about 2715 kg ha^{-1} in dry weight), equivalent to 26 kg N, 4.8 kg P and 20 kg K (based on the nutrient contents of local cattle manure) (Wang et al., 1999). These data follow the trends shown for all of China by Tong et al. (2003), but remain at a lower level.

Fertilizer use efficiency, nutrient recovery, and yield responses to fertilizers are low. This is caused by poor nutrient management, such as using inappropriate fertilizer sources, application methods, and unbalanced ratios of N:P:K. Nutrient losses by soil erosion are high (Wang, 1994; Lin et al., 1999). Ammonium bi-carbonate $(NH_4)HCO_3$ has been used as a main source of N fertilizer, which has higher NH3 volatilization and lower use efficiency than urea fertilizer (Lu and Shi, 1982). Surface application under dry soil conditions increases risks of N loss by NH_3 volatilization and by soil erosion (Wang et al., 2003c; Cai et al., 2002).

2B.3 Problems encountered with conventional tillage systems

Crop production in dryland farming is influenced by a multitude of factors ranging from climate to economy (Liu and Mou, 1988; Tao et al., 1993). The increasing population results in an increased demand for food, thus putting pressure on the land and forces farmers to increase land use intensity (Bi, 1995). The intensification of crop production contributes to a range of negative environmental effects: clean-tilled soils, unprotected for extended periods during drought, lead to land salinity and infertility and to wind erosion with an increased frequency and intensity of sandstorms (Tang, 2004; Yang et al., 2001; Wang, 2000; Wang et al., 2003). The resulting soil degradation has led to a reduction of productivity and to poverty (Tang, 2004; Yang et al., 2001). Most provinces of northern China face serious poverty problems related to poor land use management. Provinces in the North-West and the Loess Plateau remain economically the most underdeveloped regions in China, as indicated by their low ranking of Gross Domestic Product (among the nation's 31 provinces, the provinces Ningxia, Qinghai, Inner Mongolia, Gansu, Shanxi, and Shaanxi rank 30, 29, 24, 27, 22, and 21, respectively) (National Bureau of Statistics, 1999, 2003).

2B.4 *Conservation tillage practices: application and research*

2B.4.1 Indigenous conservation farming practices

Local farmers have experience in using methods to alleviate the effects of drought on crop production in the dryland farming regions of northern China (Liu and Mou, 1988; Xin et al., 2002; Li, 2004). These traditional methods include reduced tillage and no-till practices, and are known as 'sand covering cultivation' in the North-West, 'furrow-seeding or square-pit methods' in the Loess Plateau, 'ridge cultivation' in the North-East regions, and 'direct sowing in the stubble field' in the North China Plain. A brief description of these methods is given in Table 2B.5. Most of the systems are very labour-intensive.

2B.4.2 Developments in conservation tillage research

Since the 1970s soil tillage systems have changed greatly following the development and introduction of mechanized farming technologies. Research on reduced tillage and no-till systems in China was initiated in that period (Liu and Mou, 1988). The aim of the research was to develop new dryland farming technologies and to improve the traditional practices (Table 2B.5) with advanced technology. These improved practices (Liu and Mou, 1988; Wang, 1994; Xin et al., 2002) are listed in Table 2B.6. Tillage intensity or number of passes is reduced, and although individual operations may not use less energy, the total production costs are lower than conventional practices due to a reduced number of operations, less labour and a lower machinery input (Li et al., 2005).

Since the 1980s, a series of research projects on dryland farming, initiated by the Chinese Academy of Agricultural Sciences (CAAS), have been carried out in northern China. Studies on conservation tillage methods have been conducted in Shanxi in the dry semi-humid region. During 1980-1985 studies on the effects of different tillage methods on soil physical condition, soil water storage and single rainfed wheat and rainfed maize production were conducted in Tunliu (Shanxi province). During 1986-1990, the research in Tunliu focussed on the effects of alternative tillage techniques for soil water conservation. Tillage methods were developed that combined subsoiling (to break the hard pan) with mulching of straw during the summer (rainy season) fallow for rainfed wheat production, and surface residue application for rainfed maize production (Gao et al., 1990, 1991; Wang et al., 1995). During 1990-1995, studies on conservation tillage in combination with farm machinery use and agronomy in dryland farming were conducted in Linfen and Shouyang in Shanxi province (Cai et al., 1994, 1995). Compared with conventional tillage, spring maize seedling emergence was 2-3 days earlier and 17-23% higher in a dry spring but the benefit of conservation tillage was much less in a relatively wet year (Cai and Wang, 2002). The results led to recommending two sets of conservation tillage systems for spring maize in dryland areas: 1) subsoiling between rows or no-till with whole maize stalk mulching after fall harvest, and direct seeding the following spring; 2) deep ploughing with incorporated straw and fertilizers after harvest in the fall, and direct seeding of maize in spring (Table 2B.6). The two sets of conservation tillage systems have shown promising results in terms of reducing water losses and soil erosion, saving energy, increasing maize yield, and improving water use efficiency (WUE). Since the 1990s long-term field experiments on the effects of reduced tillage and residue management on nutrient cycling are being conducted in dryland farming systems in Shouyang. The results of these experiments have shown that application of crop residue was of benefit to soil protection, water conservation, soil fertility build-up, and crop yield increase (Wang et al., 2001, 2003a; Wang and Cai, 2002). However, under different weather conditions, tillage and residue management methods result in different effects. For example, straw mulching was suitable for water conservation and resulted in a yield increase in the dryland areas (such as for winter wheat in Tunliu and Linfen of Shanxi) where the annual average temperature is above 9°C. Straw incorporation, however, out competed straw mulching, in terms of improvements of water and nutrient availability, and crop yield, in those areas where the annual average temperature is low, around 7°C, as was found for spring maize in Shouyang (Wang and Cai, 2000). The surface temperature under mulch during seedling period decreased by 2-6 °C, as compared with stubble removed or incorporated (Cai et al., 2002). A study simulating soil organic carbon dynamics suggested that with conservation tillage practices on average at least 50% of the crop residue should be returned in the soil to maintain acceptable organic carbon levels. This study was based on data from 10 years of field experiments with residue, manure and fertilizer application in dryland maize production systems (Wang et al., 2005).

Other research projects on conservation tillage are underway in Hebei (Zhou et al., 2001), Qinghai (Chen et al., 2004), Shanxi (Xu et al., 2001; Wang and Wang, 1995; Min et al., 2001; Yang et al., 2004). Long-term experiments have also been carried out in international cooperative projects.

The results of these and the most important national projects are summarized in Tables 2B.7a and 2B.7b. Conservation tillage increases soil water storage (from 3 up to 50%), reduces wind erosion, increases crop yields (from 8 to 35%) and water use efficiencies (2 to 36%), saves energy and reduces labour inputs (with more than 60%), as compared to conventional tillage. Yields under no-till are equivalent to those under conventional tillage in years with an average rainfall pattern, higher in dry years (from 4 to 22%), and usually lower during wet years.

Table 2B.5 Indigenous conservation farming systems in dryland regions of northern China (based on Liu and Mou, 1988; Xin et al., 2002; Li 2004)

Region	Description of Indigenous conservation farming systems	Utilization and effects
North-West region (mainly in Gansu)	***sand covering no-till cultivation***: Small fields are covered with a layer (10-15 cm) of gravelly sand, graded from coarse at the bottom to fine near the surface. Organic fertilizers are sprayed on top, sowing without seedbed preparation with a thin (1-2 cm) covering of sand.	For spring wheat, millet, potato crop cultivation: yield up 1-2 times; water infiltration up 9 times; water content up 4-12%; salinization down 51~89%; soil temperature up 1~2 °C; crop maturity for fa and summer harvest 20-30d and 7-10d earli compared to uncovered fields
	rainwater-harvesting: collection of rainwater from the compacted surfaces or rocks, paved courtyard, rooftops. Storage in an underground cellar or kiln with capacity of 30-50 m^3.	Supplemental irrigation leads to higher yiel of wheat, maize, and cotton (up by 20-40% and allows production of cash crops.
Loess Plateau region (mainly in Shaanxi and Shanxi)	***furrow-seeding or square-pit sowing methods:*** Square-pits of 15-20cm depth and 20-30 cm width are dug on terraced or sloping land in hilly areas, organic fertilizers are applied in the pits before sowing	For maize, wheat, sorghum, millet, potato, soybeans, yields increase by 30%
North-East region (mainly in Heilongjiang, Jilin, and Liaoning)	***ridge cultivation combined with subsoiling between rows:*** building ridges 15-20 cm high and 25-30 wide; subsoiling 30-40 depth at 60-120 cm intervals	soybean - sorghum - millet rotation: main tillage only once in a three-year rotation;
	tillage in a 2-3 year rotation and harrowing: sowing after harrowing (2-4 times) at 10-15 cm depth, subsoiling every 2-3 years;	(1) wheat - coarse cereals - soybean rotatio fall ploughing for wheat, fall harrowing for coarse cereals, fall harrowing for soybean;
	reduced tillage by skipping tillage operations: depending on the field condition, main tillage operation between 2 crops will be skipped, sometimes compensated for by additional fertilization	(2) sorghum – soybean – maize - maize rotation: fall ploughing for sorghum - fall harrowing for soybean - fall ploughing for maize (2x)
North China Plain region (mainly in Beijing and Hebei)	***direct sowing in stubble***: leaving stubble 25-30 cm high, and sowing at 60cm width for maize; 20 cm width for wheat	for summer sown crop immediately after previous crop harvest, e.g. in winter wheat summer maize rotation cropping system

Table 2B.6 Improved tillage practices

improved practices	description
no-till	For all cereal crops, keeping stubble and straw / stalks as a mulch on the surface after harvest in summer or autumn. Sowing with a no-till planter combined with banded fertilizer application
subsoiling with straw mulching*	For winter wheat, keeping stubble (25-30 cm) and straw as a mulch on the surface after harvest in summer; subsoiling to 30-35 cm depth, distance between shanks approx. 60 cm; sowing without seedbed preparation combined with fertilizer application in autumn
ploughing with crop residue incorporation	For spring maize, incorporating straw and fertilizers by deep ploughing (25-28 cm depth) after harvest in autumn; no seedbed preparation before sowing with a no-till planter combined with banded fertilizer application in spring
furrow sowing	Square-pits 15-20 cm deep and 20-30 wide are made on terraced or sloping land in hilly areas. Organic fertilizers are applied in the pits before sowing
ridge-ditch subsoiling	Fields are subsoiled to 30-40 depth at 60-120 cm intervals every 2-3 years; ridges 15-20 cm high and 25-30 width are built in between the subsoiled lines. Crops are grown on top of the ridges.
stubble disking	Crop stubble remains on the field. No ploughing, seedbed preparation with a disk harrow (10-15 cm depth) immediately before sowing

* Also called as reduced tillage with subsoiling, or interval subsoiling

Table 2B.7a Research projects on conservation tillage in rainfed regions of northern China

nr.	Location & crop	Project (Year)	Reference
1	**Tunliu, Shanxi, winter wheat**	the National 7th 5-yr project (1986 -1990)	Gao et al. (1991)
2	**Linfen, Shanxi, winter wheat**	the National 8th 5-yr project (1991-1995)	Cai et al. (1995), Wang and Cai (2000)
3	**Linfen, Shanxi, winter wheat**	Sino-Australia project (1992 -2003)	Du et al. (2000), Li et al. (1997, 2000), Gao et al.(2003)
4	**Luoyang, Henan, winter wheat**	Sino-Belgium program (1998 -2003)	Cai et al. (2002), Cornelis et al. (2002), Schiettecatte et al. (2002), Wang et al. (2003b)
5	**Tunliu, Shanxi, spring maize**	the National 7th 5-yr project (1986-1990)	Gao et al. (1990), Wang et al. (2003a)
6	**Shouyang, Shanxi, spring maize**	the National 8th/10th 5-yr project (1991 -1995 /2001 -2005)	Cai et al. (2002), Wang and Cai (2005)
7	**Shouyang, Shanxi, spring maize**	the National 8th-10th 5-yr project (1991-2005)	Wang et al. (2003c, 2005)
8	**Hebei, summer maize-winter wheat**	Sino-Canada project (1991-2003)	Sun et al. (1995), Zhang et al. (2000), Jia et al. (2003), Ren et al. (2003)
9	**Yangling, Shaanxi, summer maize - winter wheat**	Shaanxi Province (2001-2003)	Yang et al. (2004)
10	**Daxing, Beijing, Summer maize**	Sino-EU project (1995 -1997)	Ding and Hann (2000), Xu and Mermoud (2001)

Table 2B.7b Summary of research findings from conservation tillage research (in comparison to conventional tillage) in rainfed regions of northern China

nr.	Fallow water storage	Yield effects	WUE	ET	Other benefit
1	49% with DP	up13-22% with DP		up 3-18% with DP	
2	40-49% with SS; 15% with NT	up 12-14% with NT/SS; up 15-33% with RM; down 5-6% with NT/SS (1994)	up 2-27% with NT/SS	down 9-11% with NT/SS	
3		up 18.5% with NT/SS	up 19% with NT/SS		**Runoff & wind erosion:** down 60% with NT/SS
4	3%-16% with NT; 2%-12% with SS	up 8-9% with SS; up 5% with NT (2001); down 9% with NT (2000)		up 1-13% with NT/SS	**Total cost:** down 93% with NT; down 58% with SS
5		up 2-21% with DP+RI; up 17-21% with RM; down 5-14% with NT	up 1-20% with DP+RI; up 15~18% with RM	up 2% with DP+RI;	
6	3-15% with DP+RI; 6-13% with NT/SS	up 11-35% with DP+RI; up 4-22% with NT/SS; down 11-14% with NT/SS (1995, wet)	up 29-36% with DP+RI; up 10~32% with NT/SS	down 2-7% with DP+RI; down 4-10% with NT/SS	**Wind erosion:** down 60-68% with DP/SS; down 79% with NT
7		up 17% with RI (11 yr average)	up 23% with RI (11 yr average)		**SOM:** up 1.2% with RI (11 yr average)
8		up10-15% with NT maize; no diff. with NT wheat, down 30% after 3yrs			**SOM%:** up 1.37, 1.47, 1.80 with NT wheat (2000, 01, 02) annually
9		up 53% with NT wheat; up 25% with NT corn			
10		up 11%-29% with RM; up11-20% with SS; no diff. with NT	up 46% with RM; up 19% with SS	down 17% with RM; down 12% with SS	

Note: WUE=water use efficiency ; ET = evapo(transpi)ration; NT=no-till; DP=deep ploughing; SS=subsoiling; RI=residue incorporated; RM=straw mulching;

2B.4.3 Regional adaptation of conservation tillage systems

The slow acceptance and adoption of conservation tillage practices may be attributed to several factors, associated with conceptual, scientific, and technological reasons. Faced with the immense pressure of human and animal population increases and a limited agricultural land base, Chinese governmental institutions and Chinese farmers have placed a high priority on food production and food security rather than on environmental protection and conservation of natural resources, with sometimes disastrous results. In northern China in particular, conservation tillage practices have to be adapted to site characteristics: climate, soil type, terrain, cropping system, and other land use at the farm. Therefore, conservation tillage system options are grouped according to four dryland zones, as shown in Table 2B.8 (Ministry of Agriculture of China, 2003; Gao et al., 2003). Each option attempts to integrate the components: post-harvest tillage, residue management, sowing techniques (machinery) and weed/pest management.

Table 2B.8 Regional options of conservation tillage systems (including tillage-related management practices of residue, fertilizer, crop rotation, water and pesticide) in northern China

Zone	Characteristics and problems	Conservation tillage system	Additional conservation measures
North-west desert	– Serious wind erosion – Desertification – Land degradation – Cold winter	– No-till fallow / subsoiling – Keeping stubble / cover crops – No-till sowing – Adding organic / inorganic fertilizers	– Windbreaks and shelterbelts
Loess plateau	– Serious water erosion – Drought – Deforestation – Infertile land	– Growing cover crops – Stubble surface cover – No-till sowing	– Terracing / contour/strip cropping – Agroforestry (alley cropping)
North-east cold region	– Short frost-free period – Serious spring drought – Water/wind erosion – Soil degradation/compaction	– Reduced till / ridge-till – Crop rotations – Keeping high stubble cover – No-till sowing – Adding organic manure	
North China plain region	– Spring drought – Summer flood – Secondary salinization – Water pollution	– Crop residue conservation – No-till sowing in mulch – Balanced fertilizer application – Weed control with herbicides	– Water-saving irrigation practices

2B.5 Conclusions

Chinese researchers are developing better dryland farming technologies for northern China by introducing new soil conservation practices and improving traditional “drought-resisting” practices with advanced technology. Since the 1980s, research efforts on conservation tillage have expanded via a large number of national and international research projects. The Chinese government, recognizing the environmental impacts of sand and dust storms, wind erosion, water erosion, and land degradation, actively promotes the application of conservation tillage practices.

The use of reduced tillage practices has shown promising results. Compared to conventional tillage, these practices have shown to increase water storage, reduce water loss and wind erosion, to improve crop yield and water use efficiency, and to save energy and labour inputs. Under no-till, mean crop yields are equivalent to those under conventional till, In dry years, crop yields tend to be higher and in wet years lower with no-till compared to conventional till. Lower crop yields with no-till in wet years have been related to a decreased soil temperature and seedling emergence.

Notwithstanding the research achievements and the promotional activities of the government, traditional cultivation with intensive ploughing and residue removal or burning, is still common practice, and considerable efforts will have to be made to accomplish widespread application of conservation tillage.

2C Dust storm erosion and its impact on soil carbon and nitrogen losses in northern China

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Summary

There is increased awareness of the environmental impacts of soil carbon (C) and nitrogen (N) losses through wind erosion, especially in areas heavily affected by dust storm erosion. This paper reviews the recent literature concerning dust storm-related soil erosion and its impact on soil C and N losses in northern China. The purpose of our study is to provide an overview of the area of erosion-affected soils and to estimate the magnitude of soil C and N losses from farmland affected by dust storm erosion.

According to the second national soil erosion remote-sensing survey in 2000, the area affected by wind erosion was 1.91 million km^2, accounting for 20% of the total land area in China. This area is expanding quickly as the incidence of heavy dust storms has greatly increased over the last five decades, mainly as a result of the intensification of soil cultivation. The economic and ecological damage caused by wind erosion is considerable. Heavily affected areas show a loss of nutrients and organic carbon in soils and the heavily degraded soils are much less productive. Compared with the non-degraded soil, the C and N contents in degraded soils have declined by 66% and 73%, respectively. The estimated annual losses per cm toplayer of soil C and N by dust storm erosion in northern China range from 53 to 1044 kg ha^{-1} and 5 to 90 kg ha^{-1}, respectively. Field studies suggest that soil losses by wind erosion can be reduced by up to 79% when farmers shift from conventional soil tillage methods to no-till. Thus shifting to no-till or reduced tillage systems is an effective practice for protecting soil and soil nutrients. Our study indicates that soil conservation measures along with improved soil fertility management measures should be promoted in dry-land farming areas of northern China. As erosion is a major mechanism of nutrient withdrawal in these areas, we plead for the development of accurate methods for its assessment and for the incorporation of erosion, as a nutrient output term, in nutrient budget studies.

Keywords: *dust storm; wind erosion; soil nutrients; northern China*

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2C.1 Introduction

Dust storm erosion in dry-land regions of northern China has become a serious problem (Quan et al., 2001). It threatens the productivity of agricultural soils, due to the loss of topsoil with valuable nutrients and organic matter (Song, 2004). With the loss of topsoil, the soil degrades and ultimately becomes non-productive. At present, as many as 2.6 million km² of land in China are classified as 'desertified' (a synonym of dryland degradation, Dregne (2002)), and this area is expanding quickly. It has been estimated that in the 1990s each year on average 2,460 km² of land turned into deserts, compared to 1,560 km² in the 1970s and 2,100 km² in the 1980s (Yang et al., 2001). The cause of the increased wind erosion and desertification ("any process that reduces or destroys the biological productivity of dryland" (UNCOD, 1978)) has been attributed to the intensification of soil cultivation and to overgrazing, leaving soils bare and unprotected by vegetation cover for increased periods, combined with periods of drought (Wang, 2000, Wang et al., 2003). Dust storm erosion leads to the loss of nutrient-rich and fine-textured soil particles from the top soil (Su et al., 2002). The eroded fine soil is deposited again kilometers away. Dust deposition may lead to the formation of sand dunes, 'bury' productive farmland and block canals and waterways (Zhang et al., 2004; Li et al., 2004). Dust storms have also been implicated in the transport of pollutants suspending in the air in areas of northern China (Zhang et al., 1993; Guo et al., 2004). Dust storm erosion contributes to the deterioration of the country's soil and nutrient resources, and is an environmental and socio-economic burden. It has been estimated that some 24,000 villages, 1,400 km of railway lines, 30,000 km of highways, and 50,000 km of canals and waterways are subject to constant threats of desertification in China (Yang et al., 2001). The impact of wind erosion on agricultural productivity in China has not been examined in detail yet. Studies in Alberta, Canada, with a climate comparable to large parts of northern China, suggest a loss in grain yield of 11 kg ha^{-1}, when 1 mm layer of soil has been removed by erosion (Larney et al., 1998).

Because of the increased awareness of environmental impacts of soil C and N loss, there is a need for reliable monitoring instruments. Regional C and N budgets may provide easy to establish overviews of hot spot erosion areas and therefore seem attractive, but nutrient losses by erosion have not been considered often in C and N nutrient budgets of agro-ecosystems. This paper reviews the recent literature concerning dust storm-related soil erosion and soil C and N losses in northern China. The objectives of our study are (i) to increase our understanding of the impacts of dust storm erosion on soil N and C losses of farmland in northern China, (ii) to assess soil C and N losses by wind erosion, and (iii) to provide suggestions for soil conservation and soil fertility restoration, and its assessment.

2C.2 Dust storms and land desertification in northern China

Dust storms are a natural phenomenon under the conditions of 1) strong wind, 2) cyclone movement and 3) a dry, loose and bare sandy soil. They occur frequently in deserts and surrounding areas (Zhang at el., 2001; Zhang et al., 2002b) and in many arid and semiarid agricultural regions (Song, 2004). Based on its reduction of the visibility in air, dust storms are conventionally classified as dust haze, blowing dust, dust storm and dust devil, with corresponding visibilities of about 10 km, 1 to 10 km, 0.5 to 1 km, and <0.5 km, respectively (Lu and Yang, 2001).

The frequency and intensity of dust storms in China have greatly increased during the last decades. For example, the number of dust devil events increased from 5 events in the 1950s to 14 events in the 1970s, and to 20 events in the 1990s (Table 2C.1). More than 50 events occurred in the period 2000–2002 (Liang, 2002). Most dust storms occur in northern China, in the dry-land areas, where the number of days with dust storms was more than 20 per year during the period 1956-2000 (Fig. 2C.1). About 58% of the country's total land area is in a climatic zone classified as arid or semi-arid (Yang et al., 2001), Land degradation affects around 80% of China's drylands (excluding extremely arid areas) which amounts to nearly one-third of the national territory. In Table 2C.2 the areas are shown per province.

A summary of areas classified according to different criteria and sources is given in Table 2C.3. According to the second national soil erosion remote-sensing survey in 2000, the area affected by erosion was 3.56 million km^2, accounting for 37.1% of the total land area in China. Approximately 45% is affected by water erosion and about 55% by wind erosion (NWR, 2002).

2C.3 Causes and effects of dust storms in northern China

The increased occurrence of intensive dust storms in northern China has been attributed to the increased incidence of dry and stormy weather conditions and to the increasing human activities. The intensification of soil cultivation, overstocking and overgrazing, and fuelwood collection have been implicated, in particular. These activities were responsible for about 85% of the total area with degraded soils. The remaining 15% is caused by road and urban construction, by sand dune movement by wind and by overuse of water resource, respectively (Zhu at al., 1989). The processes of sand movement are as follows: in suspension mode, dust (< 0.1 mm) and clay particles (< 0.002 mm) move at altitudes of up to 6 km and over distances of up to 6,000 km. The coarser sand particles are mainly transported by saltation (sand between 0.01-0.5 mm) or by creep (sand between 0.5-2.0 mm) (Yang et al., 2001). Soil particles will only be subject to movement when they are not aggregated, and not fixed to the soil matrix by cohesive forces. The damage by dust storms can be classified as caused by (i) sand burying, (ii) wind erosion, (iii) storms and strong winds, and (iv) air pollution (Zhang et al., 2002b). Severe sand storms and sand movements may bury farmland, buildings, transportation structures and waterways. Wind erosion leads to topsoil loss averaging 0.2 to 1 cm per storm event, but occasionally reaching up to 10 cm with very heavy storms (Lian, 2004). Wind erosion leads to loss of nutrients and to desertification. Strong winds may cause severe damage to trees, buildings, and the living environment of human beings and livestock, and the resulting dust clouds can reduce visibility, slow down traffic, and forces

Table 2C.1 Dust storm (dust devil) events per decade in northern China in the period 1950 to 2000.

10-year period	Events of dust storms	Main areas involved
1950s	5	Hamin of Xinjiang (1949); 23 counties of Hexi, Gansu (1952)
1960s	8	Tulufan of Xinjiang (1961)
1970s	13	Middle part of Xinjiang (1979)
1980s	14	Tulufan of Xinjiang, Middle and western part of Inner Mongolia, Yulin of Shannxi (1983); Anxi of Gansu, Hetian of Xinjiang (1986)
1990s	20	Xinjiang, Gansu, Ningxia, Inner Mongolia (1993); North west areas (1998)

Source: Huang and Niu (1998).

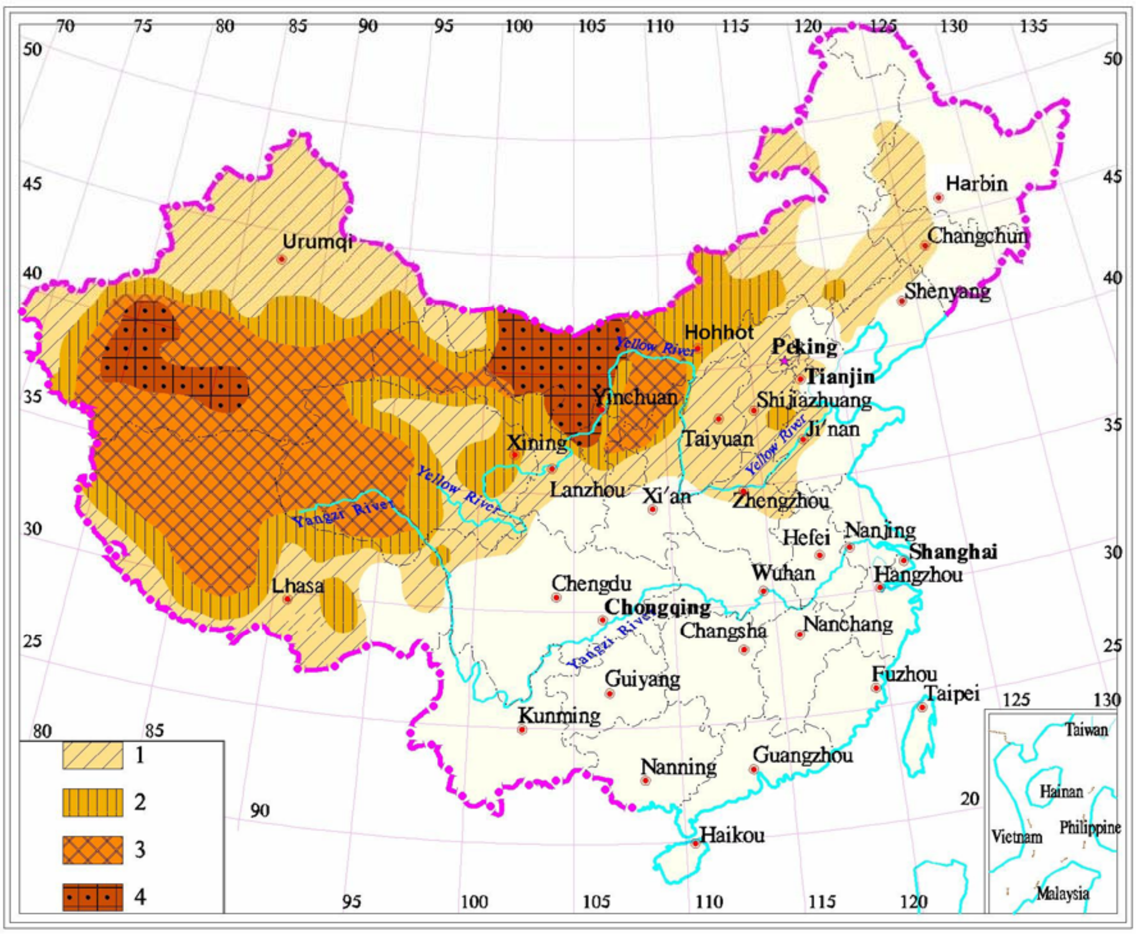

Fig. 2C.1 The annual average number of days with dust storms during 1956-2000 in China. 1: 1≤d<5; 2: 5≤d<10; 3: 10≤d<20; 4: d≥20 (d=dust storm days year^{-1}) (after Zhou et al., 2002).

Table 2C.2 The area of land affected by water erosion and by wind erosion in the provinces of China (in km^2)

Provinces	Area of water erosion	Area of wind erosion	Total
Beijing	4383	0	4383
Tianjin	463	0	463
Hebei	54662	8295	62957
Shanxi	92863	0	92863
Inner Mongolia	150219	594607	744826
Liaoning	48221	2333	50554
Jilin	19296	14278	33574
Heilongjiang	86539	8907	95446
Shanghai	0	0	0
Jiangsu	4105	0	4105
Zhejiang	18323	0	18323
Anhui	18775	0	18775
Fujian	14832	87	14919
Jiangxi	35106	0	35106
Shandong	32432	3555	35987
Henan	30073	0	30073
Hubei	60843	0	60843
Hunan	40393	0	40393
Guangdong	11010	0	11010
Guangxi	10369	4	10373
Hainan	205	342	547
Sichuan	150400	6121	156521
Guizhou	73179	0	73179
Yunnan	142562	0	142562
Tibet	62744	49893	112637
Chongqing	52040	0	52040
Shaanxi	118096	10708	128804
Gansu	119370	141969	261339
Qinghai	53137	128972	182109
Ningxia	20907	15943	36850
Xinjiang	115425	920726	1036151
Taiwan	7844	0	7844
Total	1648816	1906740	3555556

Source: MWR, 2002.

Table 2C.3 Statistical information regarding erosion-affected areas in China from various sources.

areas	1000 km^2	source
Total area China (territory)	9600	National Bureau of statistics of China, 2003
National area of arable land	1325	Bi, 1995
Total area northern China*	4860	Yang Shenghua, 1991
Area affected by erosion (total for China)	3560	MWR, 2002
(by water erosion)	1650	MWR, 2002
(by wind erosion)	1910	MWR, 2002
Area classified as "desertification affected" (total China)	2600	Yang et al 2001; SFA, 2005
by wind erosion	1840	SFA, 2005
by water erosion	259	SFA, 2005
by salinization	174	SFA, 2005
by freeze-thaw erosion	364	SFA, 2005
"Sandy desertification area"	1740	SFA, 2005
Land in arid or semi-arid climatic zone (total China)	5551	Yang et al., 2001
Drylands (excluding extremely arid areas; total China)	3300	Dregne, 2002
desert areas of China	1244	Song, 2004

* Includes the areas North-east China, Inner Mongolia, North China Plain, Loess Plateau and Gansu and Xinjiang.

airports to close. Dust storms may also contribute to air pollution as a result of various kinds of harmful and poisonous substances contained in the suspended dust in the air, thus having various health effects to humans, livestock and vegetation.

The desert areas of China, which occupy approximately 13% of China's total surface area, are major sources of Asian dust (Song, 2004). It has been estimated that about 800 Tg of dust is injected into the atmosphere in China annually, which may be as much as half of the global production of dust (Zhang et al., 1997), which is about 1000 to 3000 Tg y-1 (IPCC, 1995). It was reported that the fine particulates (PM_{10}; < 10 μm) transported by dust storms from the loess plateau have a large influence on the atmospheric environment of the northern hemisphere (Liu et al., 2004). Dust storms in northern China have impact on the atmosphere in South Korea, North Korea, Japan (Song, 2004) and Northern America (Shinn et al., 2004; Takemura et al., 2003). Dust storms also have impact on the nutrient dynamics and biogeochemical cycles of natural ecosystems, and they have a major influence on soil characteristics, oceanic productivity, and air chemistry (Washington et al., 2003).

2C.4 Soils affected by dust storms

Degraded land is mainly found on the low-fertile soils in the dry land areas of northern China. Degraded land covers a substantial part of the total arable land area in Northeast China (27%), North China (23%), Northwest China (21%), and the Loess Plateau Regions (11%), respectively (Bi, 1995). About 10 million ha of arable land in China has been affected by sand desertification since 1949 (China Water Resource News, 2001). In the affected soils, the amounts of soil organic C, and total N and P contents range from 1.7 to 4.6 g kg^{-1}, 0.2 to 0.5 g kg^{-1}, and 0.3 to 0.8 g kg^{-1}, respectively (National Soil Survey Office, 1998), as compared to the average soil organic C, and total N and P levels in North China, ranging from 3 to 7 g kg^{-1}, 0.6 to 1.0 g kg^{-1} and 0.4 to 1.0 g kg^{-1}, respectively (Bi, 1995).

Three classes of degraded farmland have been distinguished in a study on rainfed farmland of Horqin, Inner Mongolia, Northwest China (Su et al., 2002). Table 2C.4 shows that the soil organic C and N contents of the heavily degraded soil were lowest, while the percentage of silt clay (particles <0.05 mm) had dropped to below 10%. The decrease of 63% in silt content, as compared to the lightly degraded soil, suggests a massive transport of dust particles. It should be noted that the rainfed farmland of Horqin has been cultivated only for about 20 years, mainly growing legumes, buckwheat and millet crops, and some wheat and maize in the wetter places and years.

Data of Zhao et al. (2002) indicate that the soil organic C content is up to 66% lower in heavily degraded soils compared to non-degraded soils (Table 2C.5). The contents of total N, P, and K have decreased by roughly 73, 59, and 9%, respectively. (Zhao et al., 2002). These data suggest that the soil C and N contents decrease more than the P and K contents following soil degradation through wind erosion.

2C.5 Dust storm erosion and soil C and N losses from the soil

Soil cultivation has been considered as one of the most important contributors to desertification and wind erosion of farmland. In our field experiments with spring maize in Shouyang, Shanxi (Cai et al., 2002), soil losses by wind erosion were measured before sowing in April when the wind speed was 8.4 m s^{-1} at 1 m above ground surface. The results clearly show the beneficial effects of no-till (NT) relative to conventional tillage. The soil loss during an 8-hour period was up to 30 t ha^{-1} with conventional tillage (CT), compared to 6 t ha^{-1} with NT (Fig. 2C.2). As compared with CT, the soil loss was reduced by 79% and 60% to 68% with NT and other reduced tillage methods, respectively. The wind speed on the soil surface was decreased by 56% and 29%-56% with NT and with other reduced tillage methods, respectively. As such strong winds occur 1 to 5 times during spring each year (Fig. 2C.1), the soil loss by wind erosion resulting from conventional tillage methods would sum up to 30 to 150 t $ha^{-1}y^{-1}$. The estimated amounts of soil organic C and N lost each year are 409 to 2049 kg ha^{-1} and 28 to 142 kg ha^{-1}, respectively.

Table 2C.4 Characteristics of soil degradation in rainfed farmland in Horqin sandy land associated with wind erosion and desertification. Data between brackets indicate the range.

Degree of degradation	Bulk density ($Mg\ m^{-3}$)	<0.05 mm silt clay (%)	Field capacity (% moisture)	Organic C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Total P_2O_5 ($g\ kg^{-1}$)
I. Heavy	1.58 (1.53-1.63)	8.3 (6.0-10.6)	13.8 (10.6-17.2)	1.68 (1.00-2.37)	0.15 (0.14-0.20)	0.22 (0.14-0.32)
II. Moderate	1.53 (1.44-1.58)	18.3 (15.0-21.4)	21.2 (18.2-23.8)	2.56 (2.19-2.88)	0.26 (0.16-0.32)	0.34 (0.21-0.42)
III. Light	1.43 (1.34-1.53)	22.4 (16.2-27.1)	26.0 (21.4-29.4)	4.79 (3.98-5.27)	0.43 (0.33-0.58)	0.47 (0.39-0.57)

Date between brackets indicate the range.
Source: Su et al. (2002).

Table 2C.5 Changes in soil nutrient contents following soil degradation through wind erosion of sandy farmlands.

Type of soil degradation	SOC ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Total P ($g\ kg^{-1}$)	Total K ($g\ kg^{-1}$)
Non-degraded	8.58	1.03	0.32	2.70
Degraded	2.96-3.54	0.28-0.39	0.13-0.17	2.45-2.75

Source: Zhao et al. (2002)

The results of other studies undertaken in northern China are summarized in Table 2C.6. The table shows that the estimated mean amount of soil lost each year by dust storm erosion ranges from 9 to 120 t ha^{-1} . The affected soil depth is about 1 cm and the estimated soil organic C and N lost each year are 59 to 1160 kg ha^{-1} and 6 to 100 kg ha^{-1}, respectively. Li et al. (2004) report that dust input in the spring seasons is one of the sources of soil nutrition, accounting for about 1/10 of the losses of soil nutrients through wind erosion. If dust deposition is taken into account, the net losses of SOC and N were about 53 to 1044 kg ha^{-1} and 5 to 90 kg ha^{-1}, respectively.

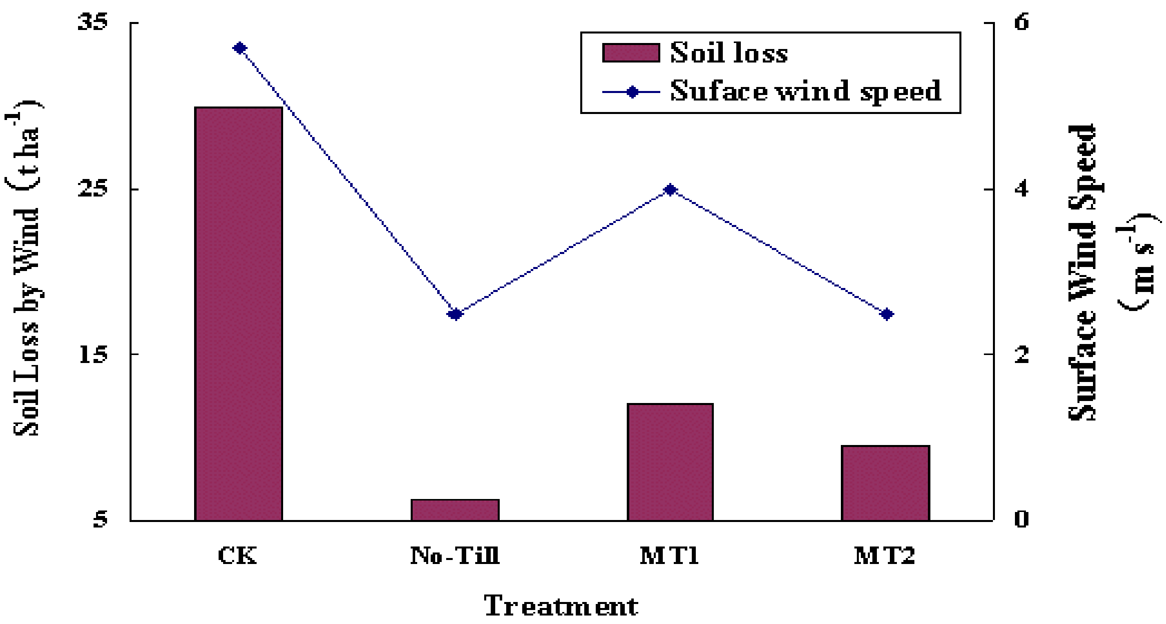

Fig. 2C.2 Impact of tillage methods on wind erosion in a corn field in Shouyang, Shanxi. CT=conventional tillage; NT=no-till; MT1=minimum tillage, plowing with corn stalk incorporated; MT2=minimum tillage, subsoiling with corn stalk mulching (Cai et al., 2002)

Table 2C.6 Estimated C and N losses from the soil affected by dust storms in northern China, using data from various case studies from different sites.

Sites in dust storm affected areas (Reference)	Affected soil depth (cm y^{-1})	Soil lost at 1-cm (t $ha^{-1}y^{-1}$)	SOC (g kg^{-1})	Total N (g kg^{-1})	C removed (kg $ha^{-1}y^{-1}$)	N removed (kg $ha^{-1}y^{-1}$)
Heilongjiang chernozems in Northeast China (Meng, 2001)	0.7-1	70-100	*2.1*	*0.26*	*147-210*	*18-26*
Liaoning in Northeast China (Zhang and Chen, 2000)	25	15	*5.2*	*0.6*	*1958*	225
Northwest China Regions (Wang et al., 2003)	2-8	68-120	*6.4*	*0.8*	*870-1536*	*170-768*
Loess Plateau Regions (Bi, 1995)	5-7				*4514*	387
Horqin sandy corn field in Inner Mongolia (Xu et al., 1993)	*>2*	44-116	*2.9*	*2.0*	*257-673*	18-46
Horqin sandy castanozems in Inner Mongolia (Zhang et al., 2002a)		9-51	5.1	0.47	59	5.9
Gansu in Northwest China (Xiao, 1998)	*>2*	106	*10.9*	*0.94*	*2320*	*200*
Shanxi of Shouyang in North China (Cai et al., 2002)	*>1*	30-150	13.8	0.96	409-2049	28-142

Note: Data in italics are estimated by the authors on the basis of data and information presented in the references. The amounts of total SOC and N lost have been calculated as follows: Loss of SOC /or N (kg $ha^{-1}y^{-1}$) = loss of soil at 1 cm (t $ha^{-1}y^{-1}$) x SOC/or N content (g kg^{-1}) x soil depth eroded (cm)*0.9 (fraction of dust nutrient deposition=10%)

2C.6 Discussion and conclusions

Dust storms are recognized as having a wide range of environmental impacts (Washington et al., 2003). They also have impact on the nutrient dynamics and biogeochemical cycles of many natural ecosystems. The studies reviewed in this paper indicate that dust storms in northern China are increasing in frequency and that there environmental impacts have also increased during the last decades. These increases in frequency and impact are related to increased soil cultivation and agricultural production.

Nutrient losses by dust storm erosion in northern China are considerable, and should be included in nutrient budgets of agro-ecosystems, especially in dust storm prone areas. The losses have increased greatly over the last decades, and erosion has become a major nutrient withdrawal mechanism in dust storm prone areas.

The loss of nutrients has been assessed via simple calculations of the depletion of nutrients in degraded soils relative to non-degraded soils. In these assessments, it is assumed that all soils contained similar amounts of nutrients before wind erosion started. However, soils are usually heterogeneous and as a result there is a fair amount of uncertainty associated with the numbers presented in this paper. Evidently, there is a need for more elaborate methods to assess the nutrient loss more accurately (Cornelis and Gabriels, 2005).

Compared with non-degraded farmland, soil organic C and total N contents in degraded soils have declined on average by 66% and 73%, respectively. Topsoil organic C and total N contents in the dust storm prone areas have decreased by 1.7 to 4.6 g kg^{-1} and 0.2 to 0.5 g kg^{-1}, respectively. The annual soil organic C and N losses by dust storm erosion in northern China have been estimated to range between 53 to 1044 kg ha^{-1} and 5 to 90 kg ha^{-1}, respectively. These estimates were corrected for dust re-deposition.

Visser et al., (2005) reported that wind erosion was responsible for losses of nutrients and fine particles in the Sahelian zone of West-Africa. Measurements and simulation using the WEPS program showed soil losses up to 115 t ha^{-1} on a degraded site. In southwest Niger on average 80 kg C ha^{-1} and 18 kg N ha^{-1} were lost annually by wind erosion (Sterk et al., 1996), mainly through saltation transport (Visser et al., 2005). These numbers are rather similar to our estimates for northern China.

Increased tillage and conventional tillage practices have been considered as the most important factors for the accelerated wind erosion and desertification. Shifting from conventional tillage to no-tillage can decrease soil losses through erosion by up to 79%, as shown by experimental measurements in the field. This suggests that no-till and reduced tillage methods can be effective practices for protecting soil and nutrients from wind erosion. Clearly, there is great need for promoting soil conservation techniques and fertility restoration management in dry land farming areas of northern China.

3 Effects of variation in rainfall on rainfed crop yields

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Manuscript

Summary

*Crop production in the dryland farming areas of northern China is constrained by low and variable rainfall. This chapter provides a detailed analysis of the relationships between the variation in monthly-seasonal-annual amounts of rainfall and yields of rainfed wheat (Triticum aestivum L.) and maize (Zea mays L.) The analysis is based on data from long-term field experiments carried out in dryland farming research projects in Tunliu, Linfen, Shouyang and Luoyang. For wheat, linear relations were found between grain yield (GY) and annual rainfall (AR), and between GY and soil water at sowing (SWS). Stepwise regressions showed significant relationships between wheat GY and SWS*SWS in Tunliu and between wheat GY and AR*AR in Luoyang. Growing season rainfall (GSR), AR, and rainfall in the month of April were critical for winter wheat GY in Luoyang. Spring maize GY in Shouyang was sensitive to June, July, and April rainfall.*

Our results indicate that possible options to alleviate occurring moisture stress for crops must be tailored to the rainfall pattern. This holds especially for tillage and farming systems and practices that aim at enhancing soil and water conservation.

Keywords: Rainfall; wheat; maize; dryland; northern China

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3.1 Introduction

Northern China has a large region of dryland farming, which accounts for about 55% of the nation's total cultivated land area (Xin and Wang, 1999). Much of the land in this region is hilly and rainfed. Water scarcity and a large variation in inter-annual and intra-annual rainfall are the main constraints to rainfed crop production, causing low and unstable food production. The annual "open pan water evaporation" varies from 1600 to 1800 mm, which is about 3-4 times the total annual rainfall in the areas. In maize (*Zea mays* L.) - wheat (*Triticum aestivum* L.) rotations, or in maize – fallow and wheat – fallow rotations, water shortages occur during maize emergence in spring and during the main period of wheat growth in late autumn and winter.

The large seasonal and annual variations in rainfall are also a cause of soil and water losses on sloping lands during the summer rainy season. On average, only 24% of the summer rainfall can be stored in the soil (Cai et al., 1995). Seasonal drought with heavy winds often occurs in winter and spring. The wind exacerbates soil drought and causes a reduction in both spring maize seedling emergence and winter wheat growth during most years.

Literature studies learn that innovative tillage systems might contribute to soil and water conservation and to improved crop yield stability. The best tillage system, for stable crop yields, is often a function of the weather experienced in that year (Lampurlanés et al., 2002). Weather conditions in the growing season also appear to play an important role in the success of no-till systems. Eckert (1984) reported that no-till maize yielded more in drier than in normal years, whereas the yields with moldboard plough systems were higher in the wetter than in normal years in the moderately well-drained soils of Ohio. In other regions, comparable results have been reported by Hussain et al (1999) for Illinois, USA, and by Riley et al (1994) for Norway. In Australia, Cantero-Martinez et al. (1995) showed the advantage of chemical fallow in years of low rainfall when better yields were the result of improved water conservation.

For the development of sustainable farming systems, that reduces the risk of crop failure, increased insights are needed on relationships between rainfall variability and crop yield variability, and on the effects of adjusted tillage and nutrient management practices on these relationships. The study presented here focuses on the relationships between rainfall and crop yield under conventional tillage and nutrient management practices at a number of sites. The field studies were carried out with winter wheat (*Triticum aestivum* L.) and spring maize (*Zea mays* L.) in dryland farming regions of northern China (Chapter 1).

3.2 Materials and methods

3.2.1 Site description

The field studies were carried out within the framework of a large national research program carried out in the period 1987 - 2001. For our purposes, data were selected from 12 studies, including the field experiments carried out at Tunliu (wheat and maize in the period 1987-1989), Linfen (wheat in the period 1992-1998), Shouyang (maize in the period 1992-2001), and Luoyang (wheat in the periods 1991-1994 and 1999-2001). All wheat-fallow and maize-fallow cropping systems were grown under rainfed conditions. The four sites (Tunliu, Linfen and Shouyang in Shanxi province, and Luoyang in Henan province, see Fig. 1.3 in Chapter 1), are located between 111°E and 113°E, and 34°N and 38°N in the dry semi-humid region of northern China in a continental monsoon climatic zone (Fig. 1.1). A more detailed description of the research sites, including the topography, soil types, cropping systems and climatic characteristics is given in Table 1.1 (see Chapter 1).

Spring maize is one of the main crops grown during the summer under the cropping system (one crop per year) in Shouyang, and accounts for over 50% of the total area under food crops. Winter wheat can be grown at other sites during the cold season, but only where the mean annual temperature is above 9°C.

The soils are Calcic Luvisols in Tunliu, Linfen, Calcaric Cambisols in Luoyang, and Calcaric-Fluvic Cambisols in Shouyang (Table 1.1). The soil fertility level in the study area is variable but rather low due to intensive cropping, low and unbalanced fertilizer input, removal of crop residues with little and uneven return of ashes and manure, and uneven wind and water erosion. Soil pH is above 8.0. Soil organic matter contents in the top soil range from 11 to 26 g kg^{-1}, Olsen - P from 6 to 25 mg kg^{-1}, and exchangeable K (NH_4OAc extractable) from 93-147 mg kg^{-1} (Table 3.1).

3.2.2 Experimental design and treatments

The field experiments were setup as randomized complete block design with two to three replications. Treatments included tillage methods, residues application and fertilizer additions, but these are not described and reported further. In the current study, the treatments with ‘conventional’ practices were selected.

The conventionally farmed plots were treated uniformly at all sites. Winter wheat was sown in late September using local varieties, and harvested in late June, followed by a summer fallow period from July to September. The wheat-seeding rate was 150 kg ha^{-1}, and the row spacing was 20 cm. Fertilizers were applied prior to seeding at rates of 150 kg N ha^{-1} and 75 kg P_2O_5 ha^{-1}, using urea and superphosphate, respectively.

Spring maize was sown in late April using local varieties, and harvested in late October, followed by a fallow period from October until the next April. The maize-seeding rate was 30 kg ha^{-1}. The inter-row and row spacing was 30x60 cm^2. Fertilizers were applied prior to seeding, at rates of 112-150 kg N ha^{-1} and 75-84 kg P_2O_5 ha^{-1}, using urea and superphosphate, respectively.

3.2.3 Measurements and calculations

Measurements and analyses included annual rainfall (AR), growing season rainfall (GSR), soil water at sowing (SWS), soil water at harvest (SWH), water use

Table 3.1 Initial soil nutrient status at the four experimental sites (0-20 cm)

Site	Total N ($g\ kg^{-1}$)	Available N (NH_4^++NO_3^-) ($mg\ kg^{-1}$)	Olsen's P ($mg\ kg^{-1}$)	Available K ($mg\ kg^{-1}$)	Organic matter ($g\ kg^{-1}$)	pH
Site 1: Tunliu, Shanxi	0.87	59	8.7		15	
Site 2: Linfen, Shanxi	0.99	57	11		11	
Site 3: Shouyang, Shanxi	0.96-1.04	54-56	1.8-7.3	93	24-26	8.5
Site 4: Luoyang, Henan	1.10	83	6.1	140	12	8.8

(expressed as evapotranspiration, ET), grain yield of wheat and maize (GY) and water use efficiency (WUE)

Rainfall during the experimental periods was measured using a rain gauge at the experimental sites. Long-term rainfall data were collected from local weather stations. The 0-200 cm soil profile was sampled before sowing and after harvest. This depth was chosen to ensure obtaining data from the maximum rooting depth. Soil moisture content was determined gravimetrically. Bulk density (BD) was determined before the start of the experiments (0 to 200 cm depth) and during the experiments (0 to 40 cm depth), using 100 cm^3 soil cores.

Water use during the growing period, expressed as evapotranspiration (ET), was calculated using the seasonal rainfall and soil water consumption data reported for each site during the growing periods. SWS and SWH (in mm) were calculated as gravimetric moisture content x BD x thickness of soil layer. Assuming no deep drainage and no runoff, the following simple equation will apply:

ET = SWS + GSR – SWH (in mm)

The crop yields of wheat and maize were determined at harvest. The WUE was calculated as GY/ET (in $kg\ ha^{-1}\ mm^{-1}$)

Statistical analysis (including stepwise regression) was conducted using the GLM and REG procedure of the SAS institute, Inc. (2004). These procedures were successfully used in crop/weather relationship studies (Chmielewski and Potts, 1995; Larsson, 1996; Mati, 2000; Salman and Al-Karablieh, 2001)

3.3 Results

3.3.1 Variation in annual rainfall

Variations in annual rainfall and growing season rainfall in Luoyang, a wheat production area and in Shouyang, a maize production area are shown in Fig. 3.1. Monthly rainfall distribution in these areas is given in Fig. 3.2. The coefficient of variation (CV) for inter-annual fluctuations in rainfall was about 22% in both Luoyang and Shouyang.

Fig 3.1a Luoyang

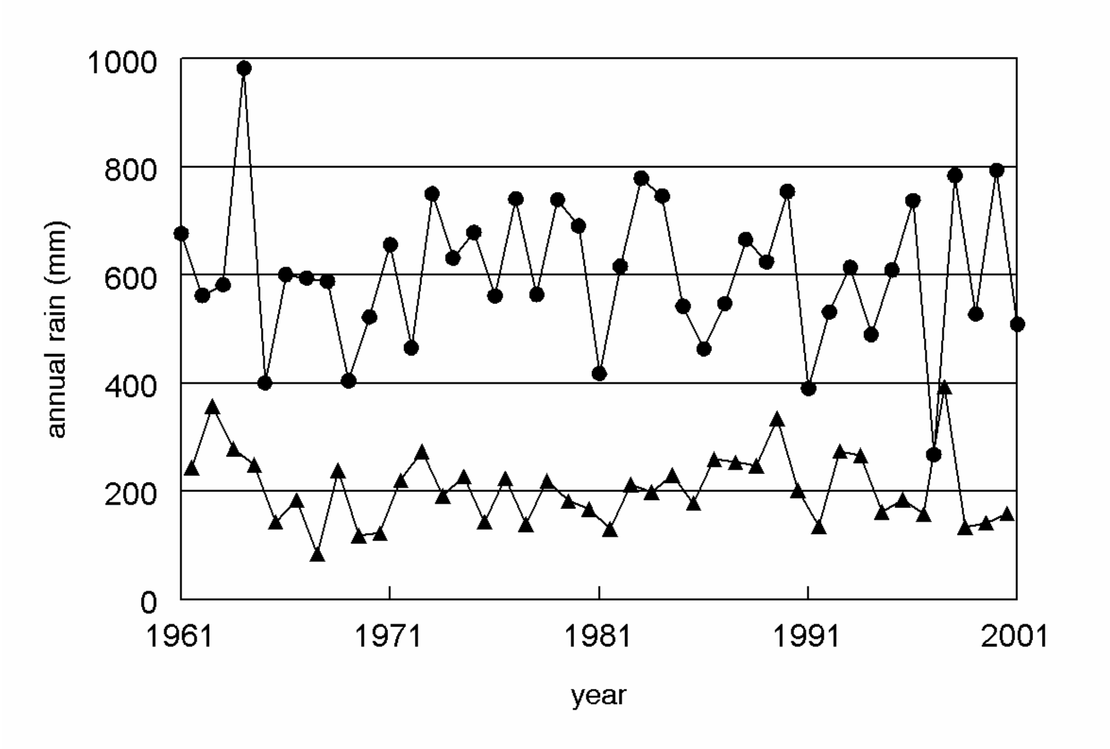

Fig. 3.1b Shouyang

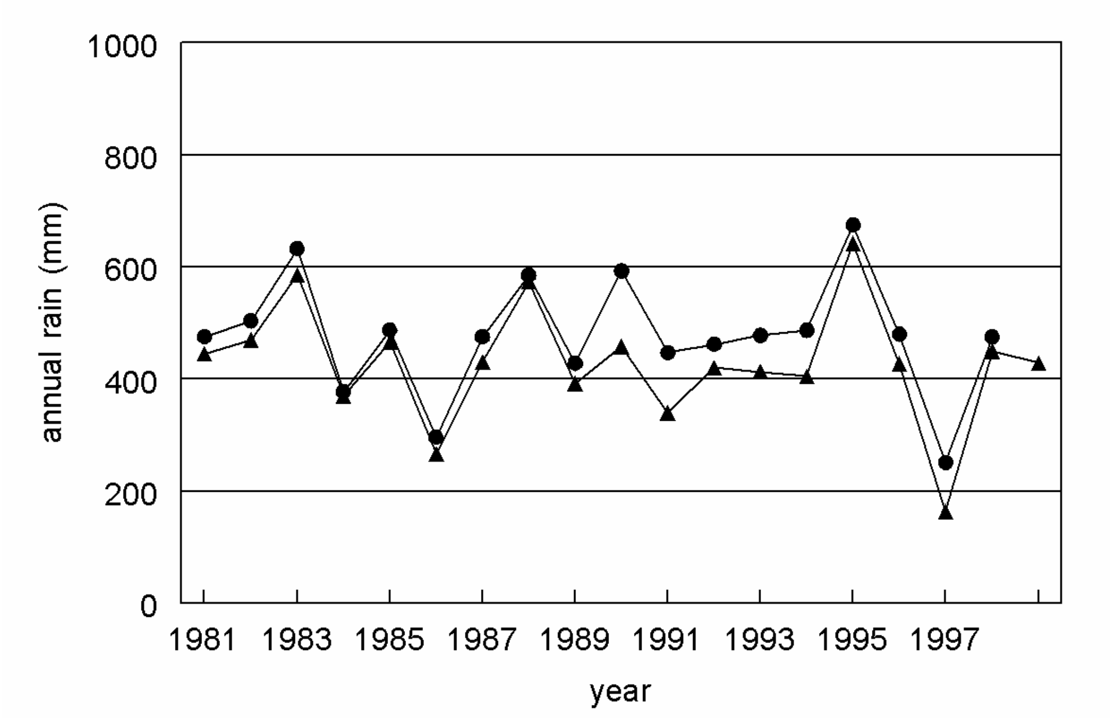

Fig. 3.1 Annual (●) and growing season (▲) rainfall in Luoyang, (1961-2001) and in Shouyang, (1981-1998).

Fig 3.2a Luoyang

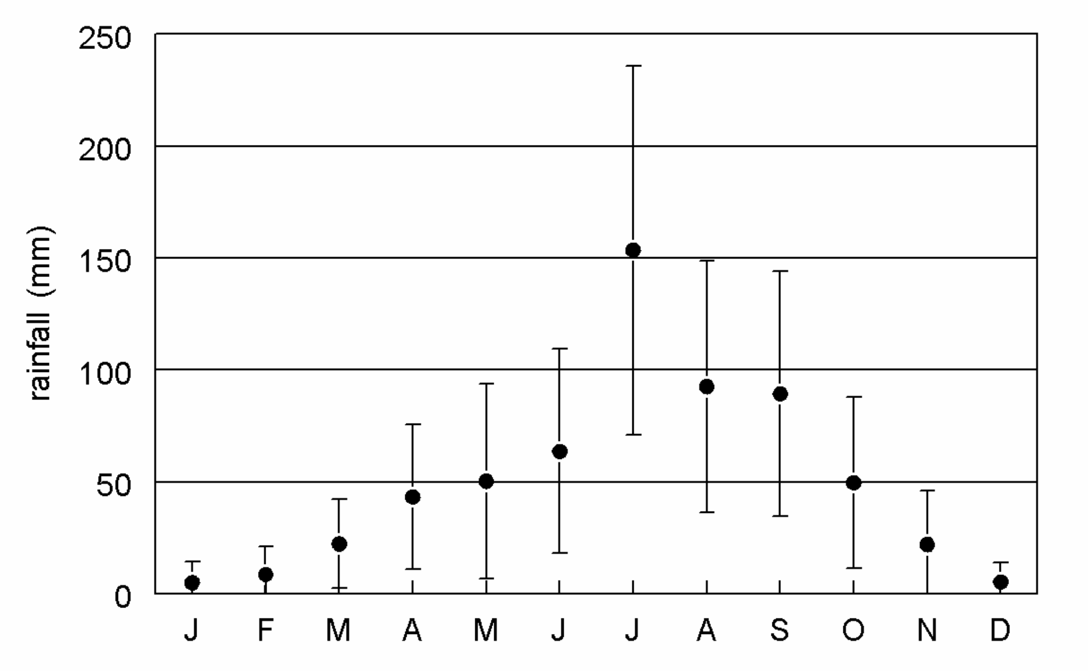

Fig. 3.2b Shouyang

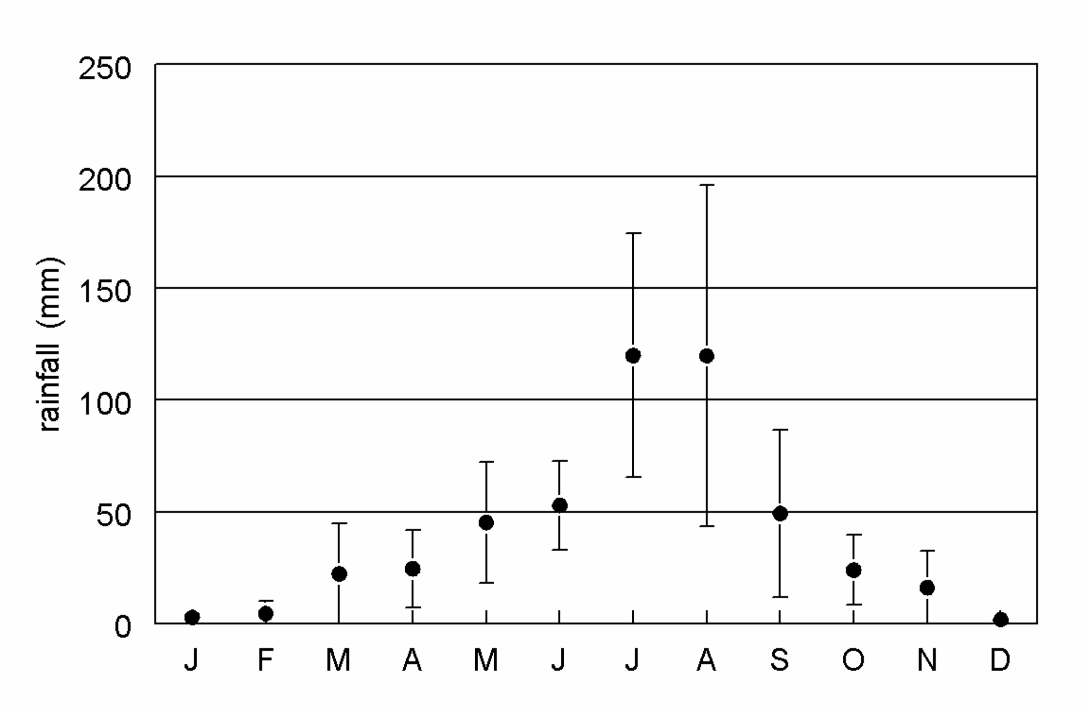

Fig. 3.2 Mean monthly rainfall distribution (●) and standard deviation (vertical bars) in Luoyang (averaged over 1961-2001) and in Shouyang (averaged over 1981-1998).

3.3.2 Variation in seasonal rainfall

During the 41-year period (1961-2001), annual average rainfall in Luoyang was 605 mm, ranging from 268 mm in 1997 to 794 mm in 2001 (Table 3.2). Rainfall in the Luoyang region is characterized by high intensities, in particular during the June – September period. Maximum daily rainfall recorded was 135 mm. Frequency of occurrence of daily rainfall > 100 mm is once in 5 year, for daily rainfall > 50 mm, this is 8 months. were recorded. Rainfall during June to September accounted for about 64% of the total annual precipitation. Rainfall peaks cause soil and water losses on sloping lands during the rainy summer season, and the uneven distribution leads to water shortages during the main period of wheat growth in winter and spring (October through May). Precipitation during this season averages 206 mm, or one-third of annual precipitation.

During the 18-year period (1981-1998), annual average rainfall in Shouyang was 478 mm, ranging from 251 mm in 1997 to 675 mm in 1995 (Table 3.3). Average rainfall during the rainy season (June to September) accounted for about 73% of the total annual rainfall. Growing season rainfall (May through October) averaged 429 mm, indicating that the growing season is rather synchronous with the rainy season (June-September). However, spring drought causes difficulty for maize seedling emergence in most years.

3.3.3 Variation in annual water use

Table 3.3 presents a summary of the results of 12 studies on water balance and crop yield, over the period 1987-2001. In these studies, conventional farming was practiced for growing wheat and maize in different cropping systems: rainfed winter wheat - fallow, and spring maize - fallow. The coefficient of variation (CV) for inter-site and inter-annual fluctuations in water use was 27% for wheat and 34% for maize. Wheat yields averaged 3586 kg ha^{-1}, but ranging from 1548 to 5126 kg ha^{-1} with AR ranging from 330 to 642 mm (Table 3.3). The GSR for winter wheat averaged 180 mm, giving a rainfall supply of on average only 40% of its water requirement. The remaining 60% (range 86 to 37%) of the water required for rainfed wheat crop must come from water stored in the soil. Water use (ET) averaged 299 mm (ranging from 184 to 431 mm), which is about 67% of the optimum water requirement, indicating that water supply during the wheat growing season was highly deficient. The importance of soil water storage was also shown by Gao et al., (1991); an increase in wheat grain yield of 123-177 kg ha^{-1} was obtained with 10 mm extra available water in the 2 m soil profile in Tunliu.

Maize yields averaged 5936 kg ha^{-1}, but ranging from 2612 to 9721 kg ha^{-1} with AR ranging from 251 to 675 mm (Table 3.3). On average, maize received 407 mm of rainfall during the growing season, varying greatly from 146 mm to 642 mm. This translates to on average 88% of the annual rain (range 32 to139%). The water use (ET) for maize averaged 423 mm (range 280 to 691 mm), which is about 92% of the water requirement, indicating that water supply during the maize growing season was sufficient under the prevailing growing conditions, except in very dry years.

Table 3.2 Average rainfall distribution (mm) in Luoyang (wheat production; period 1961-2001) and in Shouyang, (maize production; period 1981-1998)

Iterm	Luoyang	S.D.	Shouyang	S.D.
January	5	10	3	4
February	9	12	4	4
March	22	20	16	17
April	43	32	19	16
May	50	44	47	31
June	64	46	70	37
July	154	82	112	50
August	93	56	116	62
September	89	55	55	39
October	50	38	23	16
November	22	24	12	13
December	7	9	2	3
Annual Maximum (mm)	794		675	
Annual Minimum (mm)	268		251	
Annual Average (mm)	605	125	478	105
April rainfall (%) Shouyang			4	
From June to Sept. (mm)	365		353	
From June to Sept. (%)	64		73	
Growing season	206			
(Oct.-May in Luoyang) (mm)				
(May-Oct. in Shouyang) (mm)			429	
Growing season				
(Oct.-May in Luoyang) (%)	36			
(May-Oct. in Shouyang) (%)			89	

3.3.4 Relationships between grain yield and water availability

Results of correlation analyses are shown in Table 3.4. For wheat production systems, significant linear relations were found between GY and SWS, and between GY and AR. Apparent water use (ET) was linearly related to GSR, while WUE was positively related to GY and SWS, and negatively to ET and GSR.

For maize production systems, no significant relation was observed, neither between GY and precipitation factors (GSR or AR), nor between GY and SWS. The ET was linearly related to both GSR and AR, indicating that water use by maize was highly associated with rainfall.

Stepwise regression analysis by site (between wheat GY and SWS in Tunliu and between wheat GY and AR in Luoyang) resulted in the relationships shown below. All variables that remained in the model were significant at the 0.05 level; no other variable met the 0.05 significance level for entry into the model.

Wheat in Luoyang

GY = 2796.4 + 0.0010AR*AR (R^2=0.94 Prob>F 0.03);

Wheat in Tunliu

GY = 690.9 + 0.013SWS*SWS (R^2=0.91 Prob>F 0.04)

Table 3.3 Summary of the studies (under conventional farming practices); location, period and important parameters

Site	Year	AR	SWS	GSR	Water req.mnt	Rainfall supply	ET	Water supply	GY	WUE kg ha^{-1}mm^{-1}	Source
		mm	mm	mm	mm	%	mm	%	kg ha^{-1}		
Winter wheat											
Site 1: Tunliu 1	**1987-1988**	565		159	466	34	268	58	4206	15.7	Tao et al., 1993
	1988-1989		579	197	466	42	332	71	5126	15.4	
Site 1: Tunliu 2	**1987-1988**	565	439	165	466	35	201	43	3474	17.3	Wang et al., 1995
	1988-1989		532	273	466	59	431	93	4250	9.9	/Gao et al, 1991
	1989-1990		463						3152		
Site 2: Linfen	**1992-1993**	519	333	147	466	32	231	50	1548	6.7	Cai et al., 1995
	1993-1994	500	332	210	466	45	367	79	3002	8.2	
	1994-1995	434	480	133	466	29	334	72	2342	7.0	
	1995-1996	432		137	466	30	184	40	3456	18.7	Du et al., 2000
	1996-1997	574		175	466	38	257	55	3908	15.2	
	1997-1998	359		198	466	42	197	42	2495	12.7	
Site 4: Luoyang	**1991-1992**	330		137	420	33	227	54	3345	14.7	Leng and Han, 1996
	1992-1993	642		293	420	70	385	92	4950	12.8	
	1993-1994	542		280	420	67	429	102	4463	10.4	
	1999-2000	573	427	57	420	14	232	55	4248	18.3	Wang et al., 2003a
	2000-2001		288	205	420	49	363	86	3921	10.8	
Maximum		642	579	293	466	70	431	102	5126	18.7	
Minimum		330	288	57	420	14	184	40	1548	6.6	
Average		503	428	180	447	40	299	67	3586	12.7	
S.D.		95	92	65		15	82	20	972	4	
Spring maize											
Site 1: Tunliu	**1987**	538		382	458	83	405	88			Tao et al., 1993
	1988	565		489	458	107	391	85	8711	22.3	
	1989			348	458	76	401	88	7902	19.7	
Site 1: Tunliu	**1987**	538	597	387	458	84	452	99	6624	14.7	Gao et al., 1990
	1988	565	669	532	458	116	445	97	3155	7.1	
	1989		694	413	458	90			5384		
Site 3: Shouyang 1	**1992**	462	361	373	460	81	410	89	4578	11.2	Leng and Han, 1996
	1993	478	351	442	460	96	417	91	5886	14.1	
	1994	487	401	400	460	87	446	97	8789	19.7	
Site 3: Shouyang 2	**1993**	478		452	460	98	434	94	7123	16.4	Wang et al., 2003b
	1994	487	407	401	460	87	349	76	9721	27.9	
	1995	675	341	642	460	139	658	143	7164	10.9	
	1996	480	425	428	460	93	495	107	8615	17.4	
	1997	251	414	146	460	32	280	61	5025	18.0	
	1998	475	283	426	460	93	413	90	8664	21.0	
	1999		285	391	460	85	316	69	3056	9.7	
	2000		352	282	460	61	314	68	5229	16.7	
	2001		328	324	460	70	308	67	4673	15.2	
Site 3: Shouyang 3	**1993**	478	344	452	460	98	414	90	2612	6.3	Cai and Wang, 2002
	1994	487		401	460	87	479	104	5166	10.8	
	1995	675		642	460	139	691	150	5702	8.3	
	1996	480		428	460	93			4905		Li et al., 2000
	1997	251		146	460	32			4317		
	1998	475		426	460	93			7245		
	1999			391	460	85			3648		
Maximum		675	694	642	460	139	691	150	9721	27.9	
Minimum		251	283	146	458	32	280	61	2612	6.3	
Average		491	412	407	460	88	423	92	5936	15.0	
S.D.		106	128	110		24	101	22	2016	6	

Annual rainfall (AR), growing season rainfall (GSR), soil water at sowing (SWS), water use (ET), grain yield (GY) and water use efficiency (WUE)

Table 3.4 Correlation coefficients (r) for rainfed crop yield factors under conventional farming practices.

	AR	GSR	SWS	ET	GY	WUE
For Wheat						
Annual rainfall (AR)	1					
Growing season rainfall (GSR)	-0.02	1				
Soil water at sowing (SWS)	※0.86	*-0.68	1			
Water use (ET)	0.39	※0.42	0.09	1		
Wheat Yield (GY)	※0.57	-0.24	**0.83	0.34	1	
WUE	0.11	*-0.62	*0.73	*-0.57	*0.55	1
For Maize						
Annual rainfall (AR)	1					
Growing season rainfall (GSR)	**0.95	1				
Soil water at sowing (SWS)	0.17	0.11	1			
Water use (ET)	**0.82	**0.83	0.19	1		
Maize Yield (GY)	0.21	0.16	-0.07	0.18	1	
WUE	-0.32	-0.37	-0.13	-0.37	**0.83	1

Note: ※, * and ** refer to significance at P< 0.10, P< 0.05 and P< 0.01 respectively.
Annual rainfall (AR), growing season rainfall (GSR), soil water at sowing (SWS), water use (ET), grain yield (GY) and water use efficiency (WUE)

For maize, no variables met the 0.05 significance criterion for entry into the model. For wheat, the results indicate that the relations between GY and AR at Luoyang and between GY and SWS at Tunliu were nonlinear during the experimental years. GSR was not critical for wheat and maize grain yields, but water use (ET) was related to GSR, for both wheat and maize (not shown).

The relationships between ET and SWS and GSR for wheat at Linfen and for maize at Shouyang were as follows:

Wheat in Linfen
ET = -92.1 + 0.0066SWS*GSR (R^2=1.00 Prob>F 0.03);
Maize in Shouyang
ET =255.8 + 0.00095GSR*GSR (R^2=0.86 Prob>F 0.00)

Further analyses conducted on monthly and seasonal rainfall data from Luoyang showed that wheat GY was linearly related to GSR (r=0.78) and AR (r=0.70). Wheat GY was more related to April rainfall (r=0.74) than to other monthly rainfall amounts (Table 3.5). This indicates that April rainfall, coinciding with the wheat booting stage, may be the most critical parameter for wheat grain yields in Luoyang, accounting for 55% of wheat yield variability.

Analysis of monthly and seasonal rainfall data from Shouyang showed that maize GY was linearly related to monthly rainfall in June (r=0.77) and July (r=0.84). This indicates that rainfall during these two months was the most critical parameter for spring maize grain yield in Shouyang, coinciding with the maize shooting-tasseling stages. Grain yield was also related to April rainfall (r=0.58), indicating that April rainfall influences maize seedling emergence, and thereby grain yields.

Table 3.5 Correlation coefficients (r) for crop grain yield (GY) and monthly rainfall under conventional farming practices

Month	Wheat GY (in Luoyang) [1]	Maize GY (in Shouyang) [2]
January	0.14	-0.38
February	0.27	0.24
March	-0.43	-0.18
April	0.74	※0.58
May	0.49	0.13
June	-0.35	**0.77
July	0.44	**0.84
August	0.58	-0.16
September	0.51	-0.21
October	-0.05	0.37
November	0.40	-0.01
December	0.11	0.55
AR	0.70	0.38
June-Sep	0.58	0.35
Oct-May (GSR)	0.78	
May-Oct (GSR)		0.40

Note:
1) Data calculated from 5 years' wheat yields and monthly rainfall data (1991-1992, 1992-1993, 1993-1994, 1999-2000, and 2000-2001); ** r (0.01)=0.96; * r (0.05)=0.88; and ※ r (0.1)=0.81;
2) Data calculated from 10 years' maize yields and monthly rainfall data (1992-2001);
** r (0.01)=0.77; * r (0.05)=0.63; ※ r (0.10)=0.55

3.4 Discussion and conclusions

Yield potential is defined as the yield of a crop cultivar when grown in environments to which it is adapted, with nutrients non-limiting and pest and diseases effectively controlled (Evans, 1993). For a given crop variety or hybrid in a specific field environment, yield potential is determined by the amount of incident solar, temperature and plant density. Yield potential can be reduced by insufficient water supply, as is the case in the rainfed cropping systems in northern China. Here, the yield potential is water-limited, i.e., determined by the degree of water deficit, and genotype, solar radiation, temperature and plant population. In addition, actual yields are possibly influenced by the magnitude of yield loss from factors such as imbalanced nutrition, diseases, insect pests and weed competition.

This study focussed on relationships grain yield and rainfall, while assuming that other factors were constant. Though constant, the other factors may not have been optimal for the growing conditions at the experimental sites and years. Simulation models can be used for example to exploring the potentials of other genotypes and plant pollutions (plant densities) for increasing grain yield and water use efficiency (WUE) for the various experimental sites (Van Keulen and Seligman, 1987; Yang et al., 2006).

Our study shows that the rainfall distribution in dryland areas of northern China has a peak in the period June to September. The rainfall during the wheat growing season (from October to May) accounts for only one-third of the annual rainfall, indicating that water stored in the soil is crucial for wheat production. The rainfall during the maize growing season (from May to October) averages almost 90% of the total annual rainfall, indicating that the maize growing season coincides well with the rainy season. Yield variability was strongly related to inter-annual and intra-annual variations in amount and distribution of rainfall.

For wheat production systems, high linear correlations were found between wheat GY and SWS, and between wheat GY and AR. Further stepwise regressions showed significant relations between wheat GY and SWS*SWS in Tunliu and between wheat GY and AR*AR in Luoyang. The analysis of monthly rainfall showed that April rainfall at booting stage was critical for wheat grain yields in Luoyang, explaining about 55% of yield variability.

For maize production systems, June and July rainfall were the most critical for spring maize grain yield in Shouyang, when the maize crop is in the shooting-tasseling stage. A high correlation coefficient (r=0.58) between maize GY and April rainfall at maize seedling emergence was also observed. Variations in July, June, and April rainfall variability explain about 70, 59, and 34% of maize yield variability, respectively.

Water use efficiency (WUE) of wheat ranged from 6 to 19 kg ha^{-1} mm^{-1}, which is equivalent to 0.9 to 1.9 kg ha^{-1} m^{-3}. For maize, WUE ranged from 6 to 28 kg ha^{-1} mm^{-1}. A similar range of values for wheat and maize have been reported by Fan et al. (2005) for a long-term field experiment in Gansu, northwest China, with a mean annual rainfall of 540 mm, and with 60% of the total rainfall in July through September. They found strong increases in WUE (factor 4 for wheat and factor 3 for maize) through application of manure, straw and NP fertilizers. In our experiments, N and P fertilization was assumed to be adequate, but deficiencies of other nutrients (notably potassium), may have contributed to variations in GY and hence WUE.

In conclusion, wheat yields in rainfed crop production areas of northern China are sensitive to the (total) amount of annual rainfall, whereas maize yields are sensitive to the critical time of water supply (especially April, June and July rainfall). This information will help the development and adaptation of appropriate conservation tillage technologies in dryland areas of northern China. It shows the need for maximizing water storage during the rainy season for wheat production. In this respect, conservation tillage systems are recommended that will use appropriate direct drilling equipment. When the preparation of a seedbed by tillage can be avoided, moisture losses at sowing are minimized and material protecting against evaporation (such as crop residue) can remain at the soil surface.

4 Tillage and residue effects on rainfed wheat and maize production

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Manuscript

Summary

Field studies on tillage and residue management for winter wheat and spring maize were conducted at 4 sites in Shanxi and Henan provinces in the dry semi-humid regions of northern China. The effects of different tillage and residue application methods on soil physical conditions, soil water storage, water use, crop yields, and water use efficiency were assessed. Conservation tillage, comprising no-till as well as reduced tillage practices (subsoiling, deep ploughing) showed benefits which were more prominent in combination with residue application. Benefits compared to conventional tillage were found in the form of improved soil physical conditions, such as higher soil bulk densities of the topsoil, leading to a better water conservation and protection from wind erosion. Conservation tillage also improved water availability to crops, due to a better water storage and reduction of water loss during the summer fallow or rainy season. Compared to conventional methods, conservation tillage practices generally led to yield improvements. Reduced tillage gave yields around 22% higher in spring maize and round 7% higher for winter wheat. Yields under no-till were very close to those from conventional methods. Surface application of crop residue for maize may delay seedling emergence, because of low temperatures. Therefore, incorporation of residue in combination with reduced tillage is preferred. For winter wheat, subsoiling in combination with straw mulching after harvest in summer every other two or three year, and no-till seeding is a promising practice for sandy loamy soils. For heavier clay loam soils, deep ploughing with straw mulching after harvest in summer every other two or three year, and no-till seeding practice is recommended. For spring maize, deep ploughing with straw and fertilizers incorporation after harvest in fall, and no-till seeding practices are recommended. Subsoiling or no-till with residue mulching after harvest in fall, and no-till seeding practices in spring are also promising practices, the latter only in situations where low spring temperatures are not a problem.

Keywords: *conservation tillage, no-till, reduced tillage; residue management, wheat, maize, China*

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4.1 Introduction

China has a large region of dryland farming in the north, which accounts for about 56% of the nation's total area. The dry semi-humid zone (Fig. 2B.1, Chapter 2B) with 500-600 mm annual rainfall covers about half of the dryland area. In this zone, rainfed maize and wheat are the main cereals grown (Xin and Wang, 1999). Development of dryland farming in this zone is constrained by adverse weather, topography and water resource conditions, and low fertility soils. Generally, the poor soil management is not appropriate to the conditions. Much of the land is hilly. Annual precipitation shows large variations from year to year and uneven distribution within seasons. In general, around 60-70% of rainfall is concentrated during the months of June-September (Chapter 3). Spring droughts occur in most years, and summer or autumn droughts sometimes happen. The seasonal drought periods cause a reduction in both spring maize seedling emergence and winter wheat growth (the two crops most commonly grown) during most years. The soils are derived from eolian deposits (loess), and the topsoils are often eroded by wind and water erosion. The natural soil fertility is further compromised by over-cultivation and overgrazing resulting from increasing pressures on landuse because of the increasing population.

Conventional farming practices are characterized by intensive soil cultivation, low or sub-optimal fertilizer and manure inputs, and removal of crop residue. Such practices lead to unstable land productivity in these sensitive areas. The depletion of soil fertility and decline in agricultural productivity have increased environmental concerns and emphasized the need for soil conservation practices.

Since the 1980’s conservation tillage studies initiated by the Chinese Academy of Agricultural Sciences (CAAS) as part of national research projects on dryland farming, have been carried out in the dry semi-humid regions of northern China. Separate studies on rainfed crop production during 1985-1990 in Tunliu, during 1990-1995 in Linfen, and in Shouyang of Shanxi province, and during 1999-2001 in Luoyang of Henan province showed that conservation tillage practices improved water storage, crop yields, and water use efficiency.

The objective of this study was to connect and analyse the results of abovementioned studies. The effects of different tillage and residue application methods on soil physical conditions, water storage, crop yields, and water use efficiency of winter wheat and spring maize were determined. Conservation tillage was applied with the following objectives: (1) reducing the number of operations, (2) avoiding inverting tillage leaving a bare soil surface, (3) breaking up hard pans, (4) allowing crop residue to be incorporated in an effective way, or to be left at the soil surface. The results of the studies have been used to derive recommendations on the suitability of conservation tillage (no-till and reduced till) and residue management (mulching or incorporation) methods for rainfed wheat and maize production in the dry semi-humid regions of northern China.

4.2 Materials and methods

4.2.1 Site description

The locations of the research sites Tunliu (TL), Linfen (LF) and Shouyang (SY) counties of Shanxi province, and Luoyang (LY) of Henan province are shown in Fig. 1.1. A brief description of the research sites, including topography, soil type and climatic characteristics is given in Table 1.1.

Spring maize is the main crop grown under the one-crop-per-year cropping system in Shouyang. Winter wheat can be grown at other sites, where the mean annual temperature is above 9°C. The mean annual precipitation varies from 450 to 570 mm, with large variations from year to year and with uneven distributions within seasons (Chapter 3). High rain intensity and frequent rainstorms occur during the summer season (June to September) when about 60-70% of the annual precipitation occurs. The winter and spring are dry and often there are heavy winds.

The soils are sandy loams and sandy clay loams in texture. The soil nutrient levels in the area are rather low (Table 1.1). Soil pH is above 8.0. In Tunliu (Wang et al., 1995) and in Linfen (Cai et al., 1995), soils have a shallow top layer and a hard pan between 17-27 cm depth due to traditional moldboard ploughing over many years. This causes a decrease in rainwater infiltration and an increase in surface runoff during summer fallow in the rainy season. Slopes are gentle (1-3%) except for Luoyang (10%).

4.2.2 Treatments

Experiments at the different sites were carried out in a randomized (block) design, generally in 4 replications. A summary of the treatments for winter wheat is given in Table 4.1. All tillage experiments were done with medium-size tractors and commonly available equipment. Sowing in undisturbed and residue covered plots was done using a special no-till sowing machine with disk coulters. Cultivars sown were Jinmai 24 (Tunliu), Jinmai 33 or Pingyang 298 (Linfen) and Yumai 48 (Luoyang) at a rate of 150 kg ha^{-1}. Row spacing was 20 cm. Fertilizers were applied prior to seeding at rates of 150 kg N ha^{-1} as urea (112.5 kg N ha^{-1} in Linfen) and 75 kg P_2O_5 ha^{-1} as superposphate). In Luoyang, 45 kg K_2O ha^{-1} was also applied. Plot sizes were 1300, 533 and 90 m^2 in Tunliu, Linfen and Luoyang, respectively. In Tunliu and Linfen, there were sub-treatments with wheat straw mulching at a rate of 4500 kg ha^{-1}.

An overview of the treatments for spring maize is given in Table 4.2. Tillage and sowing equipment was similar to that used in the wheat experiments. The maize cultivars Zhongdan 3 (Tunliu) and Chidan 14 (Shouyang) were used, at a seeding rate of 30 kg ha^{-1}. The inter-row and intra-row spacing was 30x60 cm. Fertilizers were applied prior to seeding, in Tunliu at rates of 138 kg N ha^{-1} (urea) and 84 kg P_2O_5 ha^{-1} (superphosphate), and in Shouyang at rates of 150 kg N ha^{-1} and 75 kg P_2O_5 ha^{-1}. Plot size was 1333 m^2 in Tunliu and 390 m^2 in Shouyang. The experiment in Tunliu had a sub-treatments with maize stover mulching at 4500 kg ha^{-1}.

Table 4.1 Description of tillage treatments in the field experiments on winter wheat in Tunliu, Linfen and Luoyang.

Treatment	Description
Tunliu winter wheat	
CT: conventional	shallow ploughing (16-18 cm depth) after winter wheat harvest in summer
DP: deep ploughing	deep ploughing (25-28 cm depth) after winter wheat harvest in summer
NT: no-till/reduced till	keeping surface stubble after wheat harvest; stubble harrowing (12-14 cm depth) in summer
Linfen winter wheat	
CT: conventional	ploughing (about 18 cm depth) after winter wheat harvest; summer fallow from July to September; shallow ploughing before seeding in fall; harrowing and sowing in October. Fertilizers broadcast prior to seeding
NT: no-till	keeping wheat straw mulch on the fields after harvest; summer fallow; direct seeding with fertilization in October
SS: subsoiling	subsoiling (30-35 cm depth) between rows (at 60 cm interval), keeping wheat straw mulch after harvest; summer fallow; direct seeding with fertilization in October
Luoyang winter wheat	
CT: conventional	removing straw after harvest, ploughing (20 cm depth) and harrowing; again ploughing (20 cm depth) combined with fertilizer application in fall; harrowing and sowing
DP: deep ploughing	keeping stubble (10-15 cm long) and straw in the field after wheat harvest in summer; deep ploughing (25-30 m depth) combined with harrowing (5-8 cm depth); followed by a summer fallow; direct sowing with fertilization in fall
NT: no-till	keeping stubble (30 cm long) and straw on the surface after wheat harvest in summer; followed by a summer fallow; direct sowing with fertilizer application in fall
SS: subsoiling	keeping stubble (25-30 cm long) on the surface after wheat harvest in summer; subsoiling (30-35 cm depth) between rows (at 60 cm interval); summer fallow; direct sowing with fertilizer application in fall

Table 4.2 Description of tillage treatments in the field experiments on spring maize in Tunliu and Shouyang.

Treatment	Description
Tunliu spring maize	
CT: conventional	ploughing (22-25 cm depth) after spring maize harvest and then harrowing at 2 times in fall, and shallow ploughing, applying fertilizers and harrowing during the next spring before sowing
NT: no-till	no ploughing after harvest in fall, and using one pass seed and fertilizer application with a no-till planter in spring
DP: deep ploughing, stover incorporated	deep ploughing, (25-28 cm depth) thereby incorporating straw and fertilizers in fall
Shouyang spring maize	
CT: conventional	ploughing (22-25 cm depth) and harrowing in fall; ploughing and applying fertilizers next spring; harrowing and seeding by animal (or machinery); weed control by hand
NT-S: no-till, standing maize stalk	keeping the maize stalk standing after harvest in fall; using one pass seed and fertilizer application with a no-till planter in spring; weed control using herbicides
NT-F: no-till, whole maize stalk mulch	as NT-S, maize stalks are flattened on field
DP: deep ploughing, stover incorporated	deep ploughing (25-28 cm depth), thereby incorporating straw and fertilizers in the fall; harrowing in early spring and rolling before sowing; one pass seeding by machinery or animal
SS: subsoiling with whole stalk mulch	subsoiling between rows (at 60 cm interval), keeping whole maize stalk mulch after harvest in the fall; one pass seed and fertilizer application with a no-till planter in spring, weed control using herbicides
DP+MB: Mulch-before	as DP, mulching before seedling emergence (after sowing)
DP+MA: Mulch-after	as DP, mulching after seedling emergence

4.2.3 Measurements

Precipitation was measured on a daily base at the sites and additional data were gathered at nearby local weather stations.

Soil water was determined gravimetrically using soil samples from the 0-200 cm soil layer, taken at 20 cm depth intervals before sowing, after harvest, and during growing and fallow periods. This depth was chosen to ensure measurements of the whole rooting depth. At Luoyang, soil water contents were measured by TDR (time-domain-reflectometry) in the 0-180 cm soil layer.

Bulk density (BD) was determined before the start of each experiment (0 to 200 cm depth) and during the experiment in the 0 to 30 or 40 cm depth layer, using 100 cm^3 soil cores.

Soil water evaporation (E) during the fallow period and evapotranspiration (ET) during the growing periods were determined, using the seasonal rainfall and soil water consumption data during the fallow and growing periods, respectively. Water storage during the fallow was calculated as the change in soil water contents from the harvest of one crop to the sowing of the next. Fallow efficiency (FE) or water storage efficiency was calculated as volume of water that accumulated in the 0-200 cm soil profile during the fallow period, expressed as the percentage of rain fallen during that period. The soil water storage (SWS, in mm) is calculated as: gravimetric water content x BD x thickness of soil layer.

FE = (SWSend-SWSbegin)/fallow period rainfall * 100

The crop grain yields were determined at harvest, and dried to standard moisture content. Water use efficiency (WUE) was calculated as the ratio of yield to ET.

Statistical analysis was conducted using the GLM and REG procedure of the SAS institute, Inc. (2004).

4.3 Results

4.3.1 Soil bulk density

For winter wheat in Linfen, measurements showed lower bulk densities at 30 cm depth for both NT (no-till) and SS (subsoiling) compared to the CT treatment, both during summer fallow and before sowing (Fig. 4.1).

Intensive tillage in the CT treatment resulted in low bulk densities in the top 10 cm, and high bulk density at 30 cm depth, the latter due to compaction. Apparently both deeper tillage (SS) and no-till caused a reduction in subsoil compaction, be it by different mechanisms (mechanical loosening and avoidance of compactive forces, respectively).

For winter wheat in Tunliu (data not shown), there was no difference in the top 10 cm bulk densities among tillage treatments. The 10-20 cm bulk densities were lower under DP (deep ploughing) and NT (no-till), compared to CT (conventional tillage) after tillage for the summer fallow. The DP tillage method broke a hard pan in the 17-27 cm layer, resulting in lower bulk density (1.19-1.23 Mg m^{-3}) in DP compared CT (1.36-1.40 Mg m^{-3}). As a result, soil porosities were around 7% higher in DP compared to CT. This caused an increase in rainwater infiltration and a decrease in surface runoff during summer fallow in the rainy season (not shown).

For spring maize in Shouyang, bulk densities were higher with NT after the fall tillage treatment than with CT. During the whole year, there was little change in the bulk densities (0-10 cm) under NT treatments (Fig. 4.2). During the period between fall (ploughing after harvest) and spring, bulk densities declined by 0.32, 0.35 and 0.28 Mg m^{-3} with CT, DP (ploughing with stalk incorporated), and SS (subsoiling), respectively. After sowing, bulk densities were around 1 Mg m^{-3} with CT and DP, and about 1.14 Mg m^{-3} with NT and SS. Rolling after sowing was needed with CT and DP to increase the topsoil bulk density for a better seed-soil contact to ensure seedling emergence.

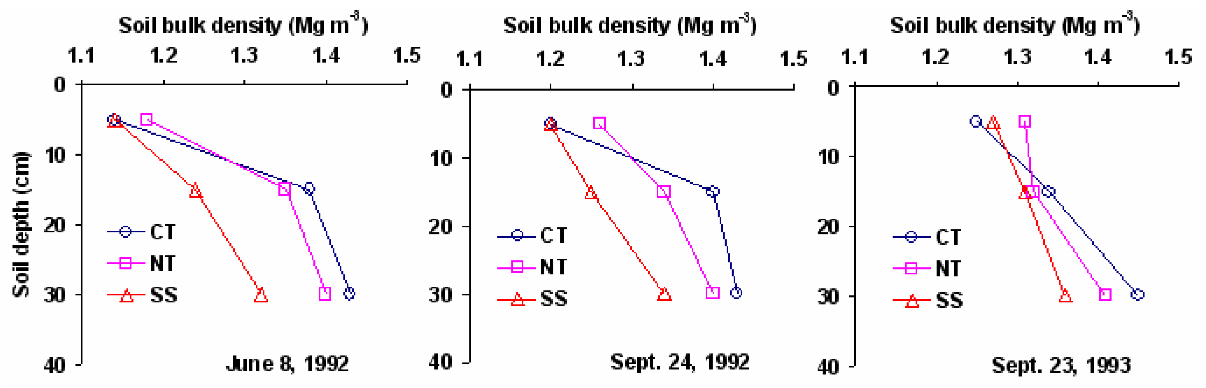

Fig. 4.1 Changes in soil bulk densities in the 0-40 cm layer during summer fallow after tillage treatment for winter wheat in Linfen (CT=conventional tillage; NT=no-till with mulching; SS=subsoiling with straw mulching).

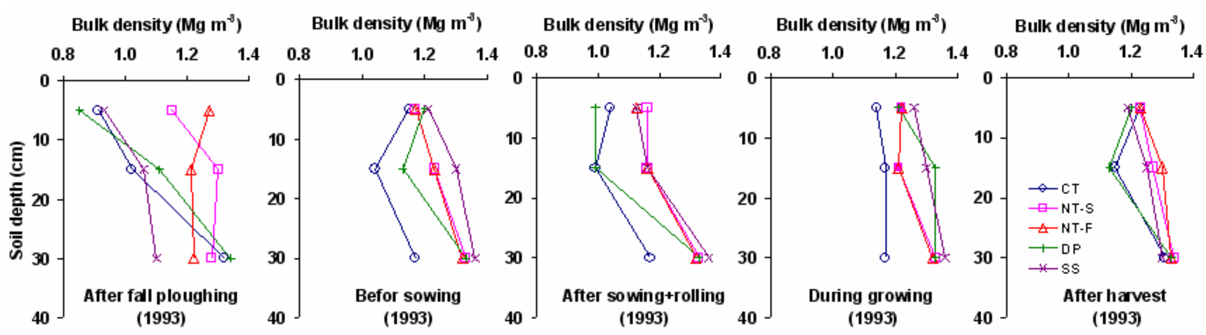

Fig. 4.2 Changes in soil bulk densities in the 0-40 cm layer in the whole year under different tillage treatments for spring corn in Shouyang (CT=conventional tillage; NT-S=no-till with standing corn stalk; NT-F=no-till with stover mulching; DP=minimum tillage with stover incorporated; SS=subsoiling with stover mulching).

4.3.2 Soil water storage

In the wheat cropping systems in Tunliu and Linfen, water storage in the soil profile (0-200 cm) was increased with all conservation tillage treatments, as shown in Table 4.3. An increase of 28 to 77 mm was found for DP, and 7 to 16 mm for NT in Tunliu. In Linfen, water storage increased with 26 to 35 mm with SS and 10 to 28 mm with NT. In Luoyang, similar improvements were measured during 1999 and 2001, but the DP treatment on the soils in Luoyang caused more water loss than did the CT treatment due to increased water evaporation during the summer fallow, which resulted in a reduction in water storage of 116 mm in 2000.

Table 4.3 Effects of tillage methods on soil water storage, evaporation (E) during summer fallow periods, and soil water at sowing (SWS) in the 0-200 cm profile of the winter wheat experiments in Tunliu, Linfen and Luoyang.

Site & Year	Treatment	Rainfall (mm)	Change in water storage (±mm)	-CT† (±mm)	E (mm)	Water storage efficiency (%)	-CT† (±%)	SWS (mm)	-CT† (±)
Site 1: Tunliu									
1987	CT	119	-55	-	174	-46	-	439	-
	DP	119	22	77	97	18	>18	488	49
	NT	119	-48	7	167	-41	6	486	47
1988	CT	207	57	-	150	28	-	532	-
	DP	207	85	28	122	41	14	546	14
	NT	207	62	5	145	30	3	558	26
1989	CT	257	65	-	193	25	-	463	-
	DP	257	111	47	146	43	18	485	22
	NT	257	80	16	177	31	6	474	11
Site 2: Linfen									
1992	CT	277	65	-	212	24	-	322	-
	NT	277	75	10	202	27	4	328	6
	SS	277	91	26	186	33	9	356	34
1993	CT	324	78	-	246	24	-	349	-
	NT	324	90	12	234	28	4	355	6
	SS	324	113	35	211	36	11	369	20
1994	CT	308	173	-	135	56	-	447	-
	NT	308	201	28	107	65	9	452	5
	SS	308	206	33	102	67	11	422	-25
Site 4: Luoyang									
1999	CT	51	-2	-	53	-5	-	426	-
	NT	51	6	8	45	12	>12	445	19
	SS	51	4	7	47	8	>8	436	10
	DP	51	-4	-2	55	-8	-3	408	-18
2000	CT	338	166	-	172	49	-	288	-
	NT	338	161	-5	177	48	-1	335	47
	SS	338	169	3	169	50	1	323	35
	DP	338	50	-116	288	15	-34	313	25
2001	CT	360	84	-	277	23	-		
	NT	360	117	34	243	33	9		
	SS	360	120	36	240	33	10		
	DP	360	65	-18	295	18	-5		

Note: †Difference from conventional tillage

On average, fallow efficiencies (FE) or water storage efficiencies were about 42% with DP, and about 30% with NT, compared to 26% with CT in Tunliu. The FE's showed a wider range in Linfen: from 27 to 65% with NT, and from 33 to 67% with SS, which were not much different from CT (24 to 56%). In Luoyang, the FE was about 33% with NT and SS compared to 24% with CT during 2001. The increased FE's with conservation tillage practices provided more available soil water for winter wheat growth, especially during dry summer fallows, when the FE were negative with CT, but still positive with DP in Tunliu during 1987 and with NT and SS in Luoyang during 1999.

Soil water contents at sowing (SWS) also increased with conservation tillage treatments, with some exceptions (1994, SS in Linfen and 1999, DP in Luoyang). These years were wetter than the other years on these sites.

Table 4.4 shows soil water contents of the soil profile, measured monthly. Under NT, soil water contents in Linfen were generally higher than with CT during the wheat growing period of March-June in both 0-100 cm and the 100-200 cm profiles. In Luoyang, soil water contents in the 0-180 cm profiles were higher with NT, both

Table 4.4 Effects of tillage methods on average monthly soil water contents (mm) during summer fallow (from July-Sept.) and wheat growing periods (from Sept.-June) (0-200 cm soil depth) in Linfen and Luoyang.

Treatment	Soil depth (cm)	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
Linfen: 1992-1994													
CT	**0-100**	176a	230a	193a	198a					184a	167a	126a	102a
NT		160a	234a	199a	196a					196a	181a	131a	115a
SS		189a	226a	203a	190a					187a	181a	135a	103a
Pr>F		NS	NS	NS	NS					NS	NS	NS	NS
CT	**100-200**	126a	164a	143a	145a					165a	157b	138a	129a
NT		126a	168a	148a	142a					171a	179a	142a	135a
SS		137a	160a	161a	155a					165a	165ab	142a	128a
Pr>F		NS	NS	NS	NS					NS	0.0454	NS	NS
CT	**0-200**	303a	394a	336a	343a					350a	324b	264a	231a
NT		286a	401a	346a	339a					366a	360a	273a	251a
SS		326a	386a	365a	345a					352a	347ab	277a	238a
Pr>F		NS	NS	NS	NS					NS	0.0637	NS	NS
Luoyang: 1999-2001													
CT	**0-180**	284c	387b	383a	381a	423b	366a	361a	345ab	321bc	254a	248c	227b
NT		319a	409a	403a	406a	438a	360ab	311b	357a	336a	259a	267a	249a
SS		299b	389b	383a	385a	424b	359ab	364a	354a	325b	272a	257b	232b
DP		285c	370c	344b	347b	408c	349ab	298b	334b	311c	252a	260b	232b
Pr>F		<.0001	<.0001	<.0001	<.0001	<.0001	NS	0.0062	0.0028	0.0002	NS	<.0001	<.0001

Note: values with the same letter within a column are not significantly different at 5% level.

during summer fallow (July-September), and during the wheat growing period (February-June). This indicated that no-till had positive effects on the sandy loamy soil.

In the maize cropping system in Shouyang (1993-1995), conservation tillage practices also increased soil water contents, as compared to CT (Table 4.5). Soil water contents with NT and SS were higher in the 0-100 cm profiles during April-September. Water contents in the 100-200 cm profiles increased with NT and SS during May-August, indicating that conservation tillage influenced the depth of soil water profile and caused increased soil water storage during the rainy season.

4.3.3 Water use, grain yield and water use efficiency

Results of tillage practices on water use, grain yield and water use efficiencies in winter wheat production systems are given in Table 4.6. In Tunliu, DP caused higher grain yields (P< 0.06) and a higher water use during the growing period, compared to CT. On the other hand, NT yields were lower in 2 out of 3 years. In Linfen, water use was lower with NT and SS than with CT (P<0.07). Straw mulching combined with NT or SS, contributed to large increases in grain yields in some years, but negative effects were observed in other years. Yield differences among tillage treatments in Linfen, were small, also when compared with conservation tillage. In Luoyang, wheat yields increased with SS during (P< 0.04), but decreased with NT in 2 out of 3 years. The NT and SS generally had a higher crop water use during the growing period, but showed only small differences in WUE.

Table 4.5 Effects of tillage methods on average monthly soil water contents (mm) during maize growing periods in Shouyang (0-200 cm soil depth). Mean results of the period 1992-1995.

Treatment	Soil depth (cm)	APR	MAY	JUN	JUL	AUG	SEP	OCT
CT	**0-100**	198b	183c	187ab	195b	204a	188b	195a
NT-S		207ab	202ab	191ab	206b	206a	199a	200a
NT-F		205ab	199ab	195a	209b	216a	207a	200a
DP		201b	191bc	183b	195b	208a	186b	202a
SS		214a	206a	189ab	234a	213a	201a	203a
Pr>F		0.0313	0.0009	0.0669	0.0013	NS	<0.0001	NS
CT	**100-200**	177a	180bc	171a	176c	227bc	191a	191b
NT-S		176a	187ab	184a	194b	243a	192a	211a
NT-F		178a	184ab	185a	194b	243a	200a	207ab
DP		183a	177c	179a	186bc	215c	179a	199ab
SS		172a	190a	180a	216a	237ab	197a	204ab
Pr>F		NS	0.0317	NS	<0.0001	0.0029	NS	NS
CT	**0-200**	375a	353b	352b	372b	428a	368a	386b
NT-S		383a	384a	365ab	395bc	438a	374a	412a
NT-F		382a	385a	376a	406b	451a	389a	406ab
DP		384a	354b	360ab	376c	429a	351a	401ab
SS		385a	386a	364ab	450a	441a	383a	408ab
Pr>F		NS	0.0493	NS	<0.0001	NS	NS	NS

Note: values with the same letter within a column are not significantly different at 5% level.

Results of tillage practices on water use, grain yield and water use efficiencies in spring maize production systems are given in Table 4.7. In Tunliu, there was little difference in water use between treatments. Residue mulching combined with conservation tillage caused an increase in water use. During the three years of the experiment, maize yields were lower with NT, and higher with DP (ploughing with stover incorporated in fall) compared to CT (P<0.00). In Shouyang, conservation tillage practices increased water use relative to CT (P<0.04), due to an increase in water storage during the rainy season, especially between June and August (data not shown). DP had the highest maize yields. NT and SS had the same positive effects in 2 out of 3 years. The timing of residue application had a large influence on maize yields in Shouyang. Yields increased with the DP+MA treatment (DP+ stover mulching after seedling emergence), but decreased with the DP+MB treatment (DP+ stover mulching before seedling emergence). This was caused by the lower soil temperature at seeding. Deep ploughing (DP) increased the WUE's for spring maize in Shouyang (P<0.08) and in Tunliu (P<0.03). Deep ploughing had significant yield advantages for spring maize, about 26% in Shouyang (6yr average) and 18% in Tunliu (3yr average), as compared with the CT treatment.

Table 4.6 Effects of tillage methods on wheat yield, ET and WUE of winter wheat crops in Tunliu, Linfen and Luoyang.

Site	Year	Treatment	Yield (kg ha-1)	-CT† (±%)	ET (mm)	-CT† (±mm)	WUE (kg mm-1ha-1)	-CT† (±)
Site1: Tunliu	**1987-1988**	**CT**	3474	-	201	-	17.3	
		DP	3927	13	237	36	16.6	-0.7
		NT	3044	-12	224	23	13.6	-3.7
	1988-1989	**CT**	4250	-	431	-	9.9	-
		DP	5189	22	446	15	11.6	1.7
		NT	4080	-4	418	-13	9.8	-0.1
	1989-1990	**CT**	3152	-				
		DP	3552	13				
		NT	3252	3				
	Pr>F		0.0551		NS		NS	
Site 2: Linfen	**1992-1993**	**CT**	1548	-	231	-	6.8	-
		NT	1736	12	207	-24	8.4	1.6
		NTM	2273	47	214	-17	10.7	3.9
		SS	1770	14	209	-22	8.6	1.8
		SSM	2351	52	212	-19	11.1	4.3
	1993-1994	**CT**	3002	-	367	-	8.3	-
		NT	2862	-5	327	-40	8.7	0.4
		NTM	3294	10	317	-50	10.4	2.1
		SS	2828	-6	334	-33	8.4	0.1
		SSM	3672	22	308	-59	11.0	2.7
	1994-1995	**CT**	2342	-	334	-	7.0	-
		NT	2153	-8	328	-6	6.6	-0.4
		SS	2621	12	353	19	7.4	0.4
	Pr>F		NS		0.0695		NS	
Site 4: Luoyang	**1999-2000**	**CT**	4218	-	232	-	18.2	-
		NT	3857	-9	234	2	16.5	-1.7
		SS	4593	9	235	3	19.5	1.3
		DP	3690	-13	203	-29	18.2	0.0
	2000-2001	**CT**	3921	-	363	-	10.8	-
		NT	4107	5	410	47	10.0	-0.8
		SS	4246	8	409	46	10.4	-0.4
		DP	4047	3	389	26	10.4	-0.4
	2001-2002	**CT**	5169	-				
		NT	4897	-5				
		SS	5480	6				
		DP	4474	-13				
	Pr>F		0.0411		NS		NS	

Note: CT=conventional tillage; DP=deep ploughing; NT =no-till with mulching; NTM= NT+mulching; SS =minimum tillage i.e., subsoiling with straw mulching; SSM= SS+mulching;
†Difference from conventional tillage

Results of mulching practices on water use, grain yield and water use efficiencies in winter wheat and spring maize production systems are given in Table 4.8. In winter wheat, residue mulching gave higher yields than CT, in Tunliu, Linfen and Luoyang. In spring maize systems, the surface residue treatments in Tunliu and Shouyang generally did not increase grain yields compared to residue-incorporation (RI). In general, residue application increased grain yields of winter wheat in Linfen and of spring maize in Shouyang and Tunliu by 16 to 26% compared to treatments without residues (-R).

Table 4.7 Effects of tillage methods on maize yield, ET and WUE of spring maize crops in Tunliu and Shuoyang.

Site	Year	Treatment	Yield (kg ha-1)	-CT† (±%)	ET (mm)	-CT† (±mm)	WUE (kg mm-1ha-1)	-CT† (±)
Site 1: Tunliu	**1987**	**CT**	6624	-	452	-	14.7	-
		NT	6105	-8	449	-3	13.6	-1.1
		DP	6753	2	453	1	14.9	0.2
	1988	**CT**	3155	-	445	-	7.1	-
		CTM	3830	21	458	13	8.4	1.3
		NT	2723	-14	450	5	6.0	-1.1
		NTM	2593	-18	485	40	5.4	-1.7
		DP	3830	21	452	7	8.5	1.4
		DPM	4496	43	459	14	9.8	2.7
	1989	**CT**	5386	-				
		NT	5111	-5				
		DP	6362	18				
	Pr>F		0.0031		NS		0.0252	
Site 2: Shouyang	**1993**	**CT**	2612	-	415	-	6.3	-
		NT_S	2993	15	399	-16	7.5	1.2
		NT_F	3188	22	386	-29	8.3	2.0
		DP	3303	26	386	-29	8.6	2.3
		SS	3092	18	375	-40	8.3	2.0
		DP+MB	2298	-12	365	-50	6.3	0.0
		DP+MA	4059	55	371	-44	11.0	4.7
	1994	**CT**	5166	-	478	-	10.8	-
		NT_S	5181	0.3	437	-41	11.9	1.1
		NT_F	5465	6	461	-17	11.9	1.1
		DP	6966	35	489	11	14.3	3.5
		SS	5462	6	450	-28	12.2	1.4
		DP+MB	4890	-5	413	-65	11.9	1.1
		DP+MA	5634	9	464	-14	12.2	1.4
	1995	**CT**	5702	-	691	-	8.2	-
		NT_S	5093	-11	653	-38	7.8	-0.4
		NT_F	4916	-14	655	-36	7.5	-0.7
		DP	6318	11	679	-12	9.3	1.1
		SS	5105	-11	681	-10	7.5	-0.7
	Pr>F		0.0053		0.0368		0.0793	

Note: CT=conventional tillage; CTM=CT+mulching
NT_S=no-till (with standing stalk); NT_F =no-till with mulching; NTM= NT+mulching
DP=minimum tillage i.e., ploughing with fertilizer and straw incorporated; DPM= DP+mulching
SS =minimum tillage i.e., subsoiling with straw mulching
MB = mulching before seedling emergence (after sowing); MA = mulching after seedling emergence
† Difference from conventional tillage

4.4 Discussion and conclusions

The tillage experiments for spring maize showed that conservation tillage, especially no-till, resulted in higher bulk densities in the top 10 cm layer after fall tillage treatments than did the conventional tillage. There was little change in the top 10 cm layer bulk density during the season and rest of the year. The bulk density with NT was suitable for seedling emergence, as compared to CT, where rolling after sowing was needed. The higher surface bulk densities with conservation tillage practices help to protect the topsoil from wind erosion and reduce water evaporation. No-till or reduced tillage practices also caused a small reduction in subsoil compaction in winter wheat.

Table 4.8 Results of the statistical analysis of grain yields, water use (ET) and water use efficiency (WUE) as affected by tillage methods and residue application types for winter wheat at Linfen, Luoyang, and Tunliu and for spring maize at Tunliu and Shouyang.

Parameter	Residue application	Winter wheat Linfen 1992-1995	Luoyang 1999-2001	Tunliu 1987-1990	Spring maize Tunliu 1987-1989	Shouyang 1993-1995†
Yield (kg/ha)	**-R**	2297b	4436ab	3506a	4851b	4402b
	R	2328b		-		
	RM	2794a	4530a	4053a	4068c	4404b
	RI	-	4070b	-	5648a	5529a
	RIM	-	-	-	5521ab	4220b
	Pr>F	0.0048	NS	NS	0.0150	0.0304
ET (mm)	**-R**	311a	298a		449	528a
	R	293ab				
	RM	284b	322a		472a	500b
	RI		296a		453a	518ab
	RIM				459a	403c
	Pr>F	0.0760	NS		NS	0.0122
WUE (kg/ha.mm)	**-R**	7.4b	14.5a		10.4ab	8.4b
	R	8.0b				
	RM	9.8a	14.1a		6.9b	9.2ab
	RI		14.3a		11.7a	10.7a
	RIM				9.8ab	10.4a
	Pr>F	0.0005	NS	-	NS	NS

*: -R = no residue applied; R =surface residue by no-till; RM = residue by mulching; RI = residue by incorporation RIM = residue by incorporation + mulching;

† yield data for spring maize in Shouyang are from 1993-1998.

Conservation tillage practices increased water storage, and reduced evaporation during wheat summer fallow for winter wheat. These practices also had positive effects on maize. The increase in available water is especially meaningful on the sandy loamy loess soil. Small differences in wheat yields among tillage treatments in Linfen indicated that effects of conservation tillage were small at this site.

Crop residue, when used in combination with reduced tillage operation or no-till increased yields and reduced evaporation losses. This was particularly true in the wheat production systems, and to a lesser degree in spring maize. A lower or negative yield response to surface mulch application was observed in Shouyang. This was attributed to the lower spring soil temperatures. Residue incorporation did show positive effects, probably because of the application of nutrients, including potassium (see also Chapters 5 and 6).

Conservation tillage, combined with residue application has shown improvements in soil physical conditions (better water conservation and soil protection from wind erosion), and increased crops yields, and thereby a higher water use and water use efficiency.

For winter wheat, our results suggest that two systems may be recommended:

1. subsoiling or no-till with straw mulching after harvest in summer every other year or once in three years, followed by a summer fallow, and direct seeding in fall with a combined seed and fertilizer application by a no-till planter, in combination with weed control by herbicides. This benefits the (sloping) sandy loamy loess soils;

2. deep plouging with straw mulching after harvest in summer, followed by a summer fallow, and direct seeding in fall with a combined seed and fertilizer application by a no-till planter. This benefits the sandy clay loamy soils, and could also be carried out once in two or three years.

   For spring maize, the following can be recommended:

1. deep ploughing, incorporating straw and fertilizers after harvest in fall, and direct seeding in spring without any soil cultivation.;
2. subsoiling or no-till with residue mulching after harvest in fall, and seeding in the next spring with a combined seed and fertilizer application by a no-till planter, in combination with weed control by herbicides.

The first recommended reduced tillage practice for spring maize, i.e., deep ploughing with incorporation of straw and fertilizers after harvest in fall, and direct seeding in spring without any prior soil cultivation, was tested in a long-term field experiment in Shouyang, as further described in Chapters 5 and 6.

5 Long-Term effects of crop residue, manure and fertilizer on dryland maize under reduced tillage in northern China: I Grain yields and nutrient use efficiencies

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Manuscript

Summary

The rapidly increasing population and associated quest for food and feed in China has led to increased soil cultivation and nitrogen (N) fertilizer use, and as a consequence to increased wind erosion and unbalanced crop nutrition. In the study presented here, we explored the long-term effects of various combinations of modest applications of maize stover, cattle manure and nitrogen (N) and phosphorus (P) fertilizer under reduced tillage practices on maize (Zea mays L.) *yield and nutrient and water use efficiencies. In a companion paper, we present the effects on nutrient balances and soil fertility characteristics. The ongoing factorial field trial was conducted at Shouyang Dryland Farming Experimental Station in northern China from 1993 onwards. The incomplete, determinant-optimal design comprised 12 treatments, including a control treatment, in duplicate.*

Grain yields and N, P, and potassium (K) uptakes and N, P and K use efficiencies were greatly influenced by the amount of rain during the growing season (GSR), and by soil water at sowing (SWS). There were highly significant interactions between GSR and added stover and manure, expressed in complex annual variations in grain yield and N, P and K use efficiencies. Annual mean grain yields ranged from 3000 to 10000 kg ha^{-1} and treatment mean yields from 4500 to 7000 kg ha^{-1}. Balanced combination of stover (3000-6000 kg), manure (1500-6000 kg) and N fertilizer (105 kg) gave the highest yield. Stover and manure were important for supplying K, but the effects differed greatly between years. Overall mean N recovery efficiency (NRE) ranged from 27 to 54%, depending on N source. NRE in wet years ranged from 50 to 90%.

In conclusion, balanced combinations of stover, manure and NP fertilizer gave the highest yield and NRE. Reduced tillage with adding stover and manure in autumn prior to ploughing is effective in minimizing labor requirement and wind erosion. The potentials of split applications of N fertilizer, targeted to the need of the growing crop (response farming), should be explored to further increase the N use efficiency.

Keywords: *maize, crop residue, dryland, fertilizer, manure, nitrogen, phosphorus, potassium, nutrient use efficiency, water use efficiency*

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5.1 Introduction

Fertilizer nitrogen (N) and phosphorus (P) uses have increased rapidly in China during the last two decades, in response to the increasing quest for food by the rapidly growing human population. On the lists of fertilizer production and consumption, China ranks number one, accounting for 22% and 25% of the world totals, respectively (FAO, 2005). From the 1980s onwards, the rate of increase of fertilizer use has been larger than the rate of increase of food production, and the gap between the growth rates has continued to widen (Ye and Rozelle, 1994). Fertilizer costs account for about 25% of the total annual expenses in crop production and for about 50% of total cost for input materials (seed, fertilizer, pesticides, machinery, irrigation), even though fertilizers are heavily subsidized (Lin et al., 1999; Ye and Rozelle, 1994). The increasing use of N and P fertilizers and the neglect of manure and wastes as valuable resources of nutrients and soil organic matter (Ju et al., 2005, Yang 2006) have contributed to unbalanced fertilization, low fertilizer use efficiency, and to eutrophication of surface waters and contamination of the environment (Zhang et al., 1995; Cao, 1996; Cai et al., 2002; Bao et al., 2005; Liu and Diamond, 2005; Ju et al., 2006).

The dryland areas of northern China are highly important for providing food and feed to the growing human and animal populations. Continuous maize (*Zea mays* L.) or wheat (*Triticum aestivum* L.), and wheat-maize rotations are the dominant cropping systems. Maize accounts for 22% of the total area of food crops, and 26% of the total food production in China (China Agricultural Yearbook, 1999). Yields of maize and wheat vary greatly from year to year, mainly because of the variable (unpredictable) rainfall and wind erosion in spring (Wang et al., 2006). These effects are exaggerated by the current practices of removing crop residues from the field after harvest, to leave the ploughed soil bare during winter, and to plough the soil again in spring after fertilizer application. These practices commonly lead to soil drying and severe wind erosion in early spring. Erosion of fertile top soil, removal of crop residues (to feed animals and to be used as fuel for cooking with only partial return of manure and ashes to the cropped land) and burning of crop residues have led to nutrient depleted soils on various places (Cai et al., 2002; Peng et al., 2006; Rees et al., 1997).

Soil conservation and improved nutrient management practices are gaining interest of Chinese research and policy communities (Wang et al., 1999, 2001, 2002, 2003c; Ju et al., 2005). There is a revival of the centuries-long tradition of recycling organic residues, but now combined with mineral fertilizers. For the humid areas of China, effects of combined applications of animal manure and inorganic fertilizers on soil fertility and crop yield have been reported by Lin and Lin (1985), Xie et al. (1987), Chen et al. (1988), Chen et al. (1993) and Liu et al. (1996). Long-term effects of combined applications of animal manure and mineral fertilizers in dryland areas have been examined by Fan et al. (2005a), Guo et al. (2001), Jiang et al. (2006), Liu et al. (2005), Yang et al. (2004), Yang et al. (2003), and Zhen et al. (2006). A step further is to combine conservation tillage with improved nutrient management practices, including also the recycling of crop residues, because increasing amounts of crop residues are left in the field, especially in areas where fossil energy is used for cooking.

The study presented here aimed at optimizing applications of NP fertilizer, cattle manure and crop residues in a continuous spring maize cropping system under reduced tillage. Reduced tillage was introduced in the study area in the early 1990s and it showed to be highly effective in decreasing soil drying and wind erosion (Cai et al., 2001; Wang et al., 2006). However, this practice required that fertilizers, crop residues and manure are applied in autumn prior to ploughing, approximately 6 months before maize is seeded. Applying fertilizers long before the crop growing season is only feasible in dry conditions where nutrient losses are minimal. The objective of our study therefore is to examine the long-term effects of combined applications of NP fertilizers, maize stover and cattle manure on maize grain yield and nutrient use efficiency under reduced tillage practices. A companion paper (Chapter 6) describes the effects of these combined applications on N,P and K balances, soil organic matter dynamics and soil fertility indices.

5.2 Materials and methods

5.2.1 Site description

The ongoing long-term field experiment started in 1992 at the Dryland Farming Experimental Station (Ministry of Agriculture) in Shouyang, Shanxi province in northern China (112°-113°E, 37°-38°N). The area has a mean altitude of 1100 m above sea level and a continental monsoon climate with an average annual rainfall of 520 mm. Severe water and wind erosion in the past has led to the formation of a hilly landscape. The winter and spring season are dry and there are often strong winds. The dominant cropping system is continuous spring maize, which accounts for over 50% of the total area for crop production. Spring drought often is a limiting factor for seed germination and the emergence and growth of spring maize.

The experimental site has a sandy loam cinnamon soil, classified as a Calcaric-Fluvic Cambisol (ISS-CAS, 2003; IUSS, 2006). At the start of the experiment in 1992, soil pH was 7.9, and organic matter and N contents were 25.7 and 1.04 g kg^{-1}, respectively. Soil fertility level was low to medium, judged on the basis of P-Olsen (7.3 mg P kg^{-1}) and NH_4OAc extractable K (2.2 mmol K kg^{-1}) in the top 20 cm soil. To make the soil mineral N status spatially uniform and low, millet was grown without nutrient application in 1992, before the actual start of the experiment.

5.2.2 Experimental design

The experimental layout was a determinant-optimal design (Xu, 1988) with 3 factors, viz. NP fertilizer, maize stover and cattle manure. The experiment comprises 12 treatments, including a control treatment, in duplicate. Fertilizer NP (ratio $N:P_2O_5$ = 1:1) applications were 0, 31, 105, 179 and 210 kg ha^{-1}. Maize stover applications were 0, 879, 3000, 5121 and 6000 kg ha^{-1}. Cattle manure applications were 0, 1500, 3000, 4500 and 6000 kg ha^{-1}. The determinant-optimal design is an algorithmically based, computer-generated design, which provides the minimal set of factors of the variance-covariance matrix and thereby the maximal efficiency of the experiment. The procedures of the design and design optimization of this study are shown in Figure 5.1 and Table 5.1. The corresponding statistical model is a quadratic equation of the form:

$$Y=b_0+ b_1X_1+b_2X_2+b_3X_3+ b_{12}X_1X_2+ b_{13}X_1X_3+ b_{23}X_2X_3+ b_{11}X_1^2+b_{22}X_2^2+b_{33}X_3^2 \quad [1]$$

Where,

Y = grain yield or nutrient uptake, in kg ha^{-1};
X_1= NP fertilizer, kg ha^{-1};
X_2= stover, kg ha^{-1};
X_3= manure, kg ha^{-1}; and
$b_0, b_1, b_2, b_3, b_{11}, b_{12}, b_{22}, b_{13}, b_{23}, b_{33}$ = coefficients

5.2.3 Methods

Plots (6 x 6 m^2) were laid down randomly in duplicate. Locally recommended maize varieties were used, i.e., Yandan No.12 in 1993-1997, Shandannong No.1 in 1998, and Jindan No.34 in 1999-2004. The N and P fertilizers were urea (46% N) and superphosphate (16% P_2O_5) in a ratio of N to P_2O_5 of 1:1. Maize stover and cattle manure were obtained from local farms. The weighted mean contents of organic matter, total N, total P (as P_2O_5) and total K were 75%, 0.63%, 0.09% and 0.72% for maize stover (ratio of N:P:K=100:6:114) and 36%, 0.96%, 0.39% and 0.74% for cattle manure (ratio of N:P:K=100:18:77), respectively. Maize stover (s), cattle manure (m) and fertilizers (f) were broadcast and incorporated into the soil after maize harvest in the fall by ploughing (20 cm deep). Seeding was done in spring, usually at the end of April, without any tillage. Maize was seeded in rows at distances of 60 cm between rows and at 30 cm within the rows. Mean plant density was 55555 per ha. Weeding was done manually twice during the growing season. Maize was harvested close to the ground using sickles and all harvested biomass was removed from the plots, usually in October. Grain yield and crop residues (rachis + stems + leaves + husks) were determined by harvesting the centre 1.8 x 2.1m^2 of the plots. Samples of grain and crop residues were oven dried at 70ºC and weighed. Harvest index (HI) was calculated as the ratio of grain to total aboveground biomass yield.

Grain and stover were analyzed for total N using the Kjeldahl method, total P using the H_2SO_4-$HClO_4$ method and total K using the HNO_3-$HClO_4$-flame photometry methods (Westerman, 1990). Plant analyses of N and P started in 1993, those of K in 1997. Soil samples for moisture determination were taken at seeding and after harvest per plot. Each sample was a composite of three random 2-cm diameter cores per plot, taken at depths of 0-10, 10-20, 20-40, 40-60, 60-80, 80-100, 100-120, 120-140, 140-160, 160-180, 180-200 cm. The total volume of soil per layer was mixed thoroughly, and subsamples were weighted before and after drying at 105 ºC.

a

Trt.	Design Matrix X1	X2	X3
1	0	0	2
2	0	0	-2
3	-1.414	-1.414	1
4	1.414	-1.414	1
5	-1.414	1.414	1
6	1.414	1.414	1
7	2	0	-1
8	-2	0	-1
9	0	2	-1
10	0	-2	-1
11	0	0	0

c

Trt.	Rates of Application (kg ha^{-1}) Fert. N	Stover	Manure
1	105	3000	6000
2	105	3000	0
3	31	879	4500
4	179	879	4500
5	31	5121	4500
6	179	5121	4500
7	210	3000	1500
8	0	3000	1500
9	105	6000	1500
10	105	0	1500
11	105	3000	3000

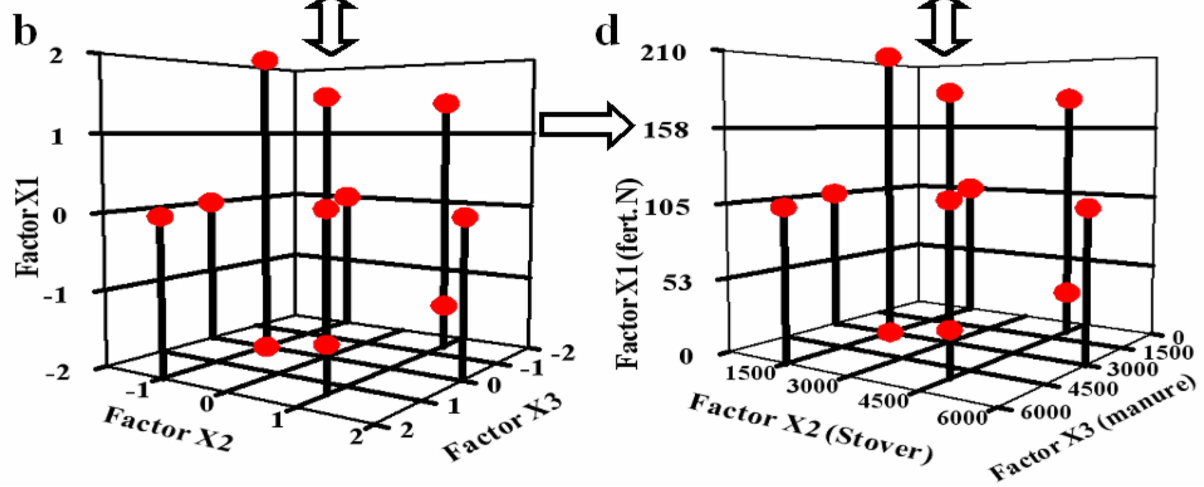

Fig. 5.1 Schematic procedure of the D-optimal 3-factor combination design: step 1, selecting a D-optimal 3-factor combination design with the minimized determinant of the variance-covariance matrix (a), and describing it as a 3-D parameter-space map (b); step 2, giving ranges of the 3 factors between max. and min., and central points (see also table 1); step 3, determining optimal levels of the factors based on the design optimization (c), and describing it again as a 3-D parameter-space map (d).

Table 5.1 Description of the calculation method for design optimization.

Range	Code	Designed Variable X1	X2	X3	Methods of calculation for design optimization X1 (Fert. N)	X2 (Stover)	X3 (Manure)
Min.	-2	0	0	0	0	0	0
	-1.414	31	879		105+52.5*(-1.414)=31	3000+1500*(-1.414)=879	
	-1			1500			3000+1500*(-1)=1500
Center	0	105	3000	3000	Z_{01}=(210+0)/2=105	Z_{02}=(6000+0)/2=3000	Z_{03}=(6000+0)/2=3000
	1			4500			3000+1500*(1)=1500
	1.414	179	5121		105+52.5*(1.414)=179	3000+1500*(1.414)=5121	
Max.	2	210	6000	6000	210	6000	6000

Note: Center: Z_{0i}=(Xi_max + Xi_min)/2 (i=1, 2, 3);

Distance: d_i=(Xi_max - Xi_min)/(Xcode_max + | Xcode_min |);

d_1=(210-0)/(2+ | -2 |)=52.5; d_2=(6000-0)/(2+ | -2 |)=1500; d_3=(6000-0)/(2+ | -2 |)=1500;

Variable: Xi=Z_{0i}+d_i*Xcode

5.2.4 Data processing and statistical analysis

Three indices for nutrient use efficiency were chosen, i.e. the additional grain yield per unit of added nutrient (agronomic efficiency, AE), the ratio of grain yield to aboveground nutrient uptake (internal utilization efficiency or physiological efficiency, PhE) and the apparent recovery efficiency (RE) of applied inputs (Moll et al., 1982; Novoa and Loomis, 1981). AE was calculated as the increase in grain yield that resulted from added nutrients relative to the control treatment, in kg grain per kg N or P applied via fertilizer, stover and manure. The apparent recovery efficiency of applied N (NRE) or P (PRE) is defined as the percentage of added N or P that is recovered in aboveground plant biomass at the end of the cropping season. For N, the equations for AE, RE and PhE read as follows.

AE = (GY_i–GY_ck)/(Nf+Ns+Nm)_i [2]

RE = 100*(Nuptake_i – Nuptake_ck)/(Nf+Ns+Nm)_i [3]

PhE = GY/Nuptake [4]

Where

GY_i = grain yield of treatment i, with i = 1 to 11, kg ha^{-1}

GY_ck = grain yield of the control treatment (treatment 12), kg ha^{-1}

Nuptake_i = the Nuptake of treatment i, kg ha^{-1}

Nuptake_ck = Nuptake of the control treatment, kg ha^{-1}

Nf_i = fertilizer N application of treatment i, kg ha^{-1}

Ns_i = amount of N in stover applied to treatment i, kg ha^{-1}

Nm_i = amount of N in manure applied to treatment i, kg ha^{-1}

Apparent water use or apparent evapotranspiration (ET, in mm) was calculated from the change in soil water contents between the beginning of the growing season at seeding (SWS, in mm) and the end of the growing season at crop harvest (SWH, in mm) plus rainfall received during the growing season (GSR), viz.

ET = (SWS-SWH) +GSR [5]

Hence, we assumed that there were no losses via deep drainage and runoff during the growing season. Apparent water use efficiency (WUE, in kg mm^{-1}) was calculated from GY and ET, according to.

WUE = GY/ET [6]

Statistical analyses were done using GLM, REG and RSREG procedures of the SAS Institute, Inc. (2004). Mean responses of grain yield (GY) and N, P and K uptakes to added NP fertilizer, maize stover and cattle manure were calculated using Equation 1. In addition, stepwise multivariate regression analyses were carried out. Linear and nonlinear (parabolic) statistical models were fitted to describe the relationships between GY and nutrient uptake on the one hand and added nutrients via fertilizer, crop residues and manure applications and GSR and SWS on the other hand.

5.3 Results

5.3.1 Variation in rainfall and soil water

During the 12-year experimental period (1993-2004), annual rainfall ranged from 251 mm in the dry year 1997 to 675 mm in the wet year 1995. On average, rainfall during the growing season (GSR) accounted for 89% of the annual rainfall, indicating that the growing season for maize (May-October) is well-synchronized to the rainy season (June-September). However, annual variations in GSR were large, ranging from 146 mm in 1997 to 642 mm in 1995 (Figure 5.2), and soil water shortage at sowing due to spring drought often occurred. Dry conditions at seeding impede seedling emergence and generally lead to low grain yield and nutrient uptake by maize (Cai et al., 1994). Apparent water use (ET) by maize ranged from a mean of 280 mm in 1997 to a mean of 660 mm in 1995 (Figure 5.2).

5.3.2 Mean grain yield and N, P and K uptake

Mean grain yield and N, P and K uptakes in aboveground biomass per treatment are shown in Table 5.2. Note that treatments are in the order of increasing GY. The control (treatment 12) had the lowest GY and N, P and K uptakes, and treatment 9 (with F=105, S=6000, and M=1500 kg ha^{-1}) the highest GY and also the highest N, P and K uptakes. Clearly, balanced combinations of NP fertilizer, stover and manure gave the highest mean yield, and the slight differences in GY between treatments 6, 11, 1 and 9 (the four treatments at the bottom of Table 5.2) were not statistically significant. Doubling NP fertilizer applications and halving the stover application (comparison of treatments 7 and 9) gave statistically significant lowering of GY, suggesting above optimal N application and below optimal K application in treatment 7 (see below).

Calculated mean responses of GY and N, P and K uptakes according to the regression equation pertinent to the design of the experiment (Eq. 1) are shown in Figure 5.3. The regression coefficients for linear and quadratic effects of added NP fertilizer were all highly significant, but the mean effects of added manure and stover were not statistically significant (not shown). There were also no statistically significant interactions between added NP fertilizer, stover and manure in mean GY and N, P and K uptakes when using Eq. 1. Figure 5.3 shows that added stover and manure had larger relative effects on K uptake than on GY and N and P uptakes. Also, maximum K uptake was obtained at NP fertilizer application rates of about 100 kg per ha, while maximum GY and N and P uptakes were obtained at NP fertilizer application rates of 150-200 kg per ha, when no stover and/or manure was applied. When combined with stover and manure, the required amounts of NP fertilizer for reaching maximum K uptake were larger than in the case of using only NP fertilizer. Conversely, the required amounts of NP fertilizer for obtaining maximum GY and N and P uptakes were smaller than in the case of single applications of NP fertilizer. These results indicate that the soil was responsive to N, P and K applications; a response to K was not foreseen at the start of the experiment.

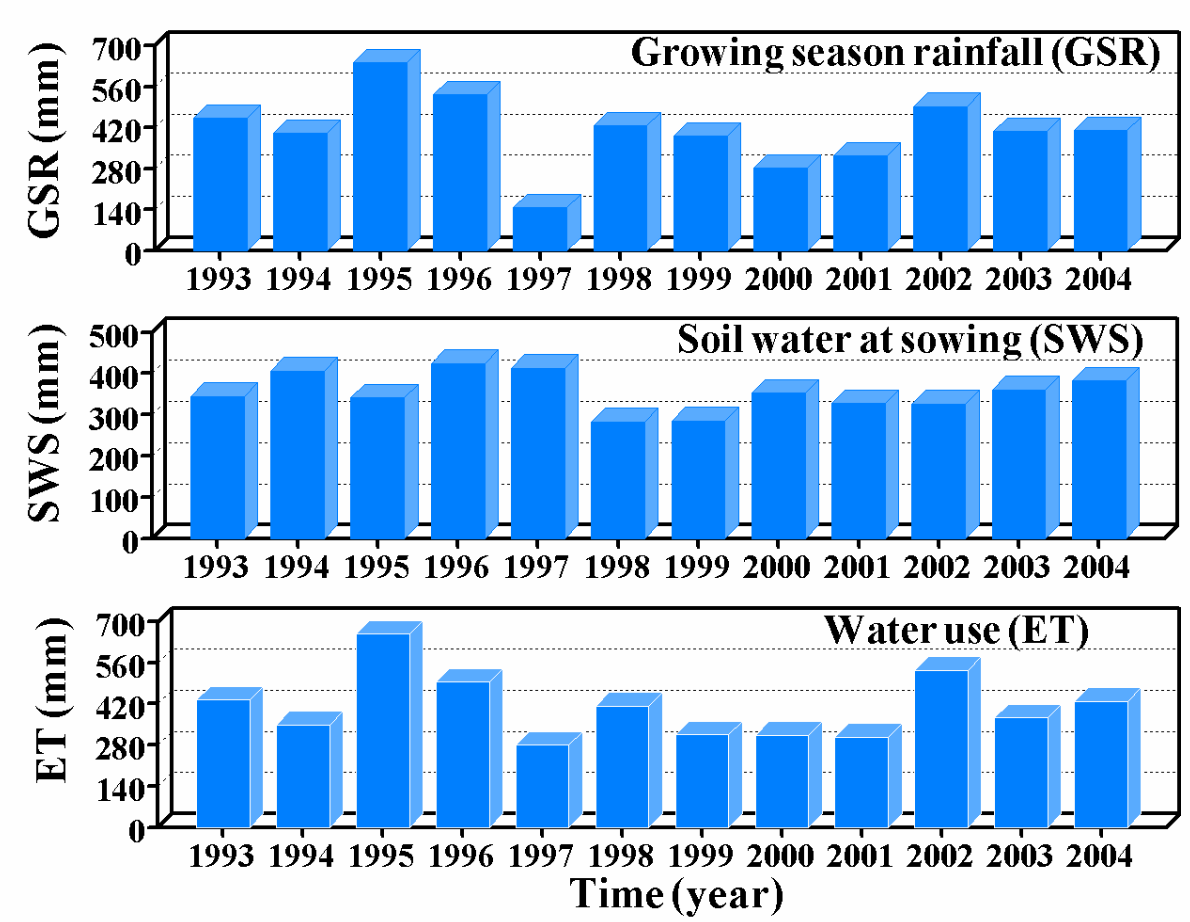

Fig. 5.2 Annual growing season rainfall (GSR), average amounts of soil water in the upper 2 m at sowing (SWS), and apparent water use (ET), in Shouyang during the experimental period 1993 to 2004.

Mean harvest index (HI) ranged from 47 to 52%, with highest values at intermediate GY (Table 5.2). Mean N recovery efficiency (NRE) in aboveground biomass ranged from 28 to 54%, and apparent N recovery in the grain (GNRE) from 18 to 35%. Variations between years within treatments were relatively large and only few treatments had statistically significant differences in NRE and GNRE. Mean P recovery efficiency (PRE) in aboveground biomass ranged from 10 to 85%, and GPRE from 8 to 62%. Highest NRE and PRE was in treatment 8 with combined applications of stover and manure, but without added NP fertilizer.

Mean apparent water use (ET) did not vary much among treatments (range 400 to 425 mm), and as a consequence, water use efficiency (WUE) varied greatly between treatments (Table 5.2). Lowest WUE (11 kg per ha per mm available water, or 1.1 kg ha^{-1} m^{-3}) was found in the control treatment and the highest WUE (19 kg per ha per mm available water, or 1.9 kg ha^{-1} m^{-3}) in treatment 9. This range (1.1 – 1.9 kg ha^{-1} m^{-3}) is similar to the range (1.1 – 2.0 kg ha^{-1} m^{-3}) measured in a long-term maize field experiment with various fertilization treatments in Gansu in China (Fan et al., 2005a).

Table 5.2 Effects of combined applications of NP fertilizer (F), maize stover (S) and manure (M) on grain yield (GY), Harvest Index (HI), uptake of N, P and K in aboveground biomass, Apparent N and P Recovery Efficiencies (NRE and PRE in aboveground biomass and GNRE and GPRE in grain), N Agronomic Efficiency (NAE) and Water Use Efficiency (WUE) per treatment, averaged over the whole experimental period (1993-2004).

Tmt.	F, kg ha^{-1}	S, kg ha^{-1}	M, kg ha^{-1}	GY kg ha^{-1}		HI kg kg^{-1}		N Uptake kg ha^{-1}		P Uptake kg ha^{-1}		K Uptake kg ha^{-1}	
12	0	0	0	4587	E	0.47	D	84.3	E	11.7	E	40.0	E
8	0	3000	1500	5139	D	0.47	CD	101.8	D	14.8	D	50.4	D
3	31	879	4500	5805	C	0.50	ABCD	117.6	C	16.8	CD	50.0	D
10	105	0	1500	6269	BC	0.51	AB	143.1	B	19.2	BC	54.1	CD
4	179	879	4500	6420	B	0.51	AB	147.7	AB	21.3	AB	61.2	BC
5	31	5121	4500	6433	B	0.52	A	128.1	C	18.8	BC	57.6	CD
7	210	3000	1500	6512	B	0.52	A	150.9	AB	21.1	AB	55.6	CD
2	105	3000	0	6528	B	0.50	ABC	146.3	AB	19.1	BC	54.2	CD
6	179	5121	4500	6668	AB	0.50	ABCD	154.1	AB	22.0	A	63.6	BC
11	105	3000	3000	6740	AB	0.49	ABCD	150.1	AB	20.8	AB	68.2	B
1	105	3000	6000	7114	A	0.48	BCD	160.2	A	22.1	A	76.8	A
9	105	6000	1500	7184	A	0.47	CD	158.4	A	22.1	A	78.3	A

Tmt.	NAE kg kg^{-1}		GNRE %		NRE %		GPRE %		PRE %		WUE kg ha^{-1} mm^{-1}		ET mm	
12	-		-		-		-		-		11.4	E	400.1	B
8	19.2	A	32.1	A	54.3	A	62.4	A	84.7	A	13.7	D	424.6	A
3	17.3	A	29.5	A	43.4	A	20.9	BC	25.2	BC	14.7	CD	410.5	AB
10	15.7	A	35.0	A	51.7	A	13.1	BCD	16.1	BCD	14.5	CD	400.9	B
4	8.4	B	18.4	B	28.0	B	9.3	CD	11.2	CD	15.9	BC	411.4	AB
5	17.4	A	30.9	A	41.2	AB	27.3	B	30.5	B	16.8	AB	403.2	B
7	8.3	B	18.4	B	27.6	B	8.2	CD	9.9	CD	16.9	AB	412.6	AB
2	15.9	A	33.9	A	50.1	A	13.2	BCD	16.2	BCD	15.4	BCD	413.1	AB
6	8.5	B	18.0	B	27.6	B	9.8	CD	11.8	BCD	17.0	AB	412.3	AB
11	14.7	A	28.6	A	43.4	A	14.8	BCD	17.5	BCD	16.2	BC	414.2	AB
1	14.1	AB	27.4	AB	41.5	AB	15.2	BCD	18.3	BCD	16.8	AB	417.4	AB
9	17.1	A	30.3	A	47.5	A	17.4	BC	20.6	BC	18.8	A	401.4	B

Note: Values with the same letter within a column are not significantly different at 5% level

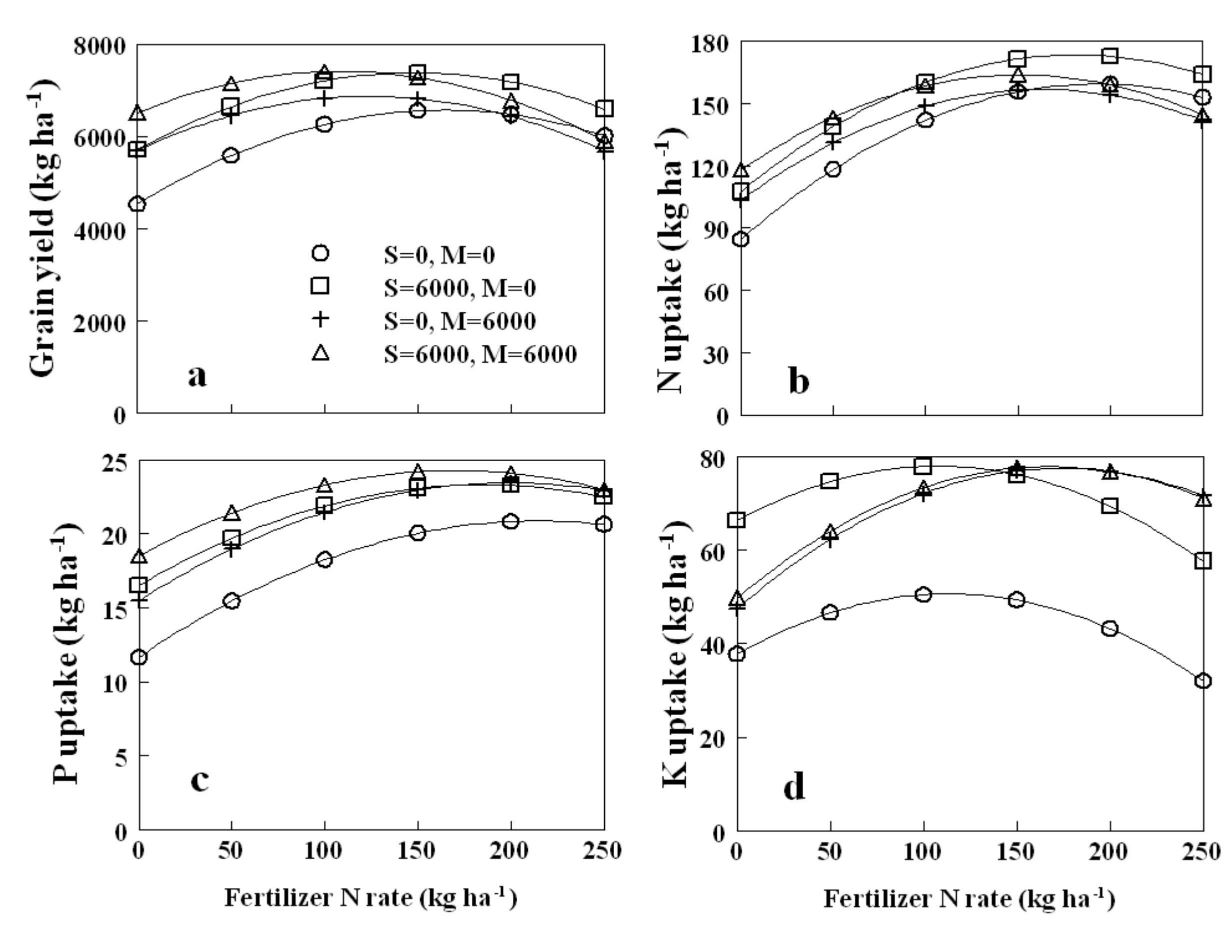

Fig. 5.3 Calculated average grain yield (GY), and plant N, P and K uptake responses to NP fertilizer (F), with and without maize stover (S: kg ha^{-1}) or manure (M: kg ha^{-1}) inputs during the period of 1993-2004 using RSREG statistical models (Eq 1):
1) GY = 4527 + 24.9F + 0.16S + 0.05M -0.08F^2; (R^2 = 0.11, n = 288)
2) N uptake = 84.6 + 0.77F + 0.005S + 0.002M -0.002F^2 (R^2 = 0.27, n = 288);
3) P uptake = 11.7+ 0.09F + 0.001S + 0.001M -0.0002F^2 (R^2 = 0.14, n = 288);
4) K uptake = 37.8 + 0.23F + 0.004S + 0.001M -0.001F^2 (R^2 = 0.20, n = 192).
Note: Coefficients of b_{12}, b_{22}, b_{13}, b_{23}, and b_{33} were not significant (see text).

5.3.3 Annual variations in grain yields

Annual variations in grain yield were large, ranging from about 3,000 in the dry year 1999 to more than 10,000 kg ha^{-1} in treatments with balanced fertilization in the wet years 1994, 1996 and 1998 (Figure 5.4). Yields were related to GSR and also to soil water content at seeding (SWS). Grain yields in all treatments tended to decrease with time during the experimental period, especially in the control treatment (treatment 12). Differences in GY between the control treatment and the treatment with the second lowest GY (treatment 8 with f=0, s=3000, m=1500 kg ha^{-1}) were absent during the first seven years (1993-1999), but were about 35% during the last five years (2000-2004) of the experiment.

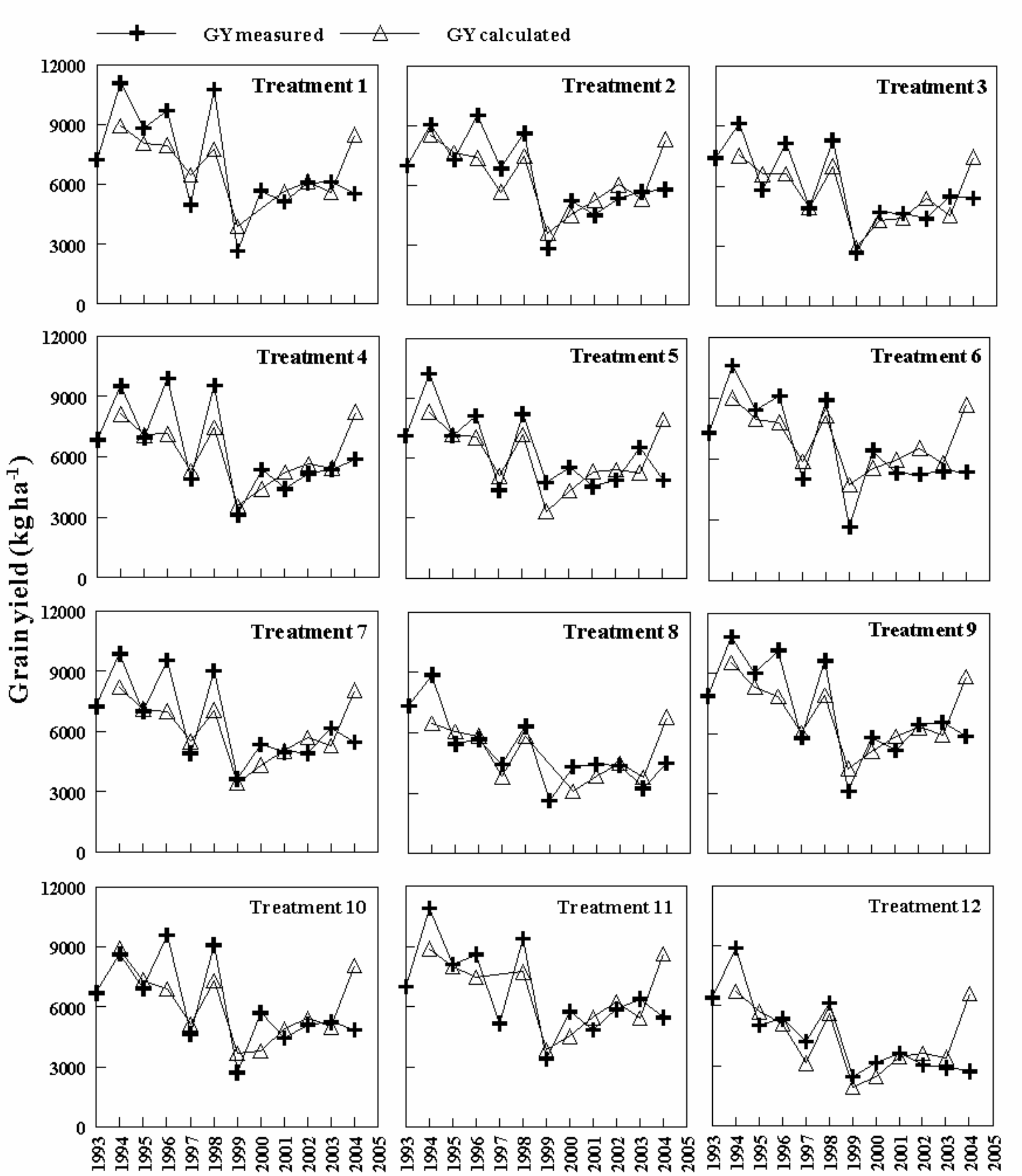

Fig. 5.4 Measured and calculated maize grain yields per treatment and year. Grain yields were calculated (GY-calculated) as function of added NP fertilizer (F), maize stover (S) and manure (M), and the amounts of soil water at seeding (SWS) and rainfall during the periods April-June (R(A-J)), July (R(J) and August-October (R(A-O), for the whole experimental period 1993-2004, according to GY = - 5140 + 24.9F + 0.14S + 0.07M + 7.13 R(A-J) + 23.5R(J) + 3.17R(A-O) + 15.4SWS - 0.09F^2 (see table 5.3).

Statistical analyses indicated that annual variations in GY per treatment were related to added fertilizer, stover and manure, and especially to GSR and SWS. Grain yield appeared highly sensitive to rainfall in July (at tasseling). Highest percentage of explained variance in GY (up to 88%) was obtained when the data set was split in wet (93, 94, 95, 96, 98) and dry years (97, 99, 00, 01, 02, 03, 04), and GY related to GSR and SWS, and added fertilizer, stover and manure. For dry years, GY was significantly related to SWS (but not to GSR) and to added fertilizer, stover and manure. In addition, there was a statistically significant interaction between added NP fertilizer and manure. For wet years, GY was significantly related to SWS and GSR (linearly and quadratic), and NP fertilizer, but not to added stover and manure (results not shown). These results would suggest that added manure and stover are important especially for dry years.

For the whole experimental period, differences in GY between treatments and between years were related to added fertilizer, stover and manure, and to SWS and the rainfall during the periods April-June, July and August-October (Figure 5.4; Table 5.3). This model could also explain satisfactorily the decreasing trend in GY over the experimental period. Fan et al (2005a, 2005b) also observed decreasing trends in maize (and wheat) yields in a long-term field experiment, which they ascribed to changing soil properties, decreasing trends in GSR and their interactions. The similar trends in measured and calculated GY (Figure 5.4) suggest that the decreasing trend in GY in our experiment is mainly related to the changes in rainfall during the periods April-June, July and August-October. Overall, the statistical model tended to underestimate GY in wet years and overestimate GY in dry years. The large difference between measured and calculated GY in 2004 is possibly related to N losses prior and during the growing season and to diseases (head smut).

Water use efficiency (WUE) ranged from 4 kg ha^{-1} m^{-3} (equivalent to 40 kg ha^{-1} mm^{-1} of rainfall) in treatments with balanced nutrient inputs in dry 1997 to 0.65 kg ha^{-1} m^{-3} (6.5 kg ha^{-1} mm^{-1} of rainfall) for the control treatments in wet 1999, 2002 and 2004 (Figure 5.5). There was a factor 5 difference in apparent water use (ET) between extremely dry 1997 and extremely wet 1995, while GY differed by only a factor of 1 to 2. Conversely, similar ET in 1994 and 2004 (about 430 mm) was accompanied with a factor 2 to 3 differences in GY. Evidently, there were additional factors involved in causing the large annual GY differences than simply GSR and SWS. The control treatments usually had the lowest WUE and treatments with balanced nutrient inputs the highest WUE in almost all years.

Table 5.3 Coefficients of the regression models for grain yield (GY), N, P and K uptakes in aboveground biomass, and NRE, as function of NP fertilizer (both linear and quadratic), maize stover, and manure, soil water at sowing (SWS) and rainfall during the periods April-June (R(A-J)), July (R(J) and August-October (R(A-O), for the whole experimental period 1993-2004.

Dependent Variable	Parameter*)	Intercept	Fertilizer	Stover	Manure	R(A-J)	R(J)	R(A-O)	SWS	Fsq
GY	PE	-5140	24.9	0.14	0.07	7.13	23.5	3.17	15.4	-0.09
R^2=0.58,	SE	1213	6.4	0.07	0.07	3.39	2.71	1.47	2.80	0.03
N = 129	tValue	-4.24	3.9	2.01	1.0	2.1	8.70	2.16	5.51	-3.02
	Pr>|t|	<.001	0.001	0.047	0.32	0.04	<.001	0.03	<.001	0.003
N uptake	PE	-24.6	0.79	0.003	0.001	-0.001	0.36	0.08	0.14	-0.003
R^2=0.48	SE	26.6	0.14	0.001	0.002	0.07	0.06	0.03	0.06	0.001
N = 129	tValue	-0.93	5.68	1.75	0.91	-0.02	6.12	2.49	2.29	-3.95
	Pr>|t|	0.36	<.001	0.08	0.36	0.99	<.001	0.01	0.02	0.001
P uptake	PE	-16.8	0.10	0.0005	0.000	-0.05	0.11	0.01	0.05	-0.0003
R^2=0.58	SE	4.54	0.02	0.000	0.000	0.01	0.01	0.006	0.01	0.000
N = 128	tValue	-3.69	4.06	1.83	1.57	-4.15	10.6	2.59	5.16	-2.67
	Pr>|t|	0.001	<.001	0.07	0.12	<.001	<.001	0.01	<.001	0.009
K uptake	PE	5.46	0.29	0.002	0.001	-0.04	0.30	0.04	-0.003	-0.001
R^2 = 0.76	SE	20.2	0.05	0.001	0.001	0.03	0.04	0.03	0.04	0.0003
N = 93	tValue	0.27	5.37	4.11	2.05	-1.29	8.59	1.01	-0.08	-4.72
	Pr>|t|	0.79	<.001	<.001	0.04	0.20	<.001	0.31	0.94	<.001
NRE	PE	29.7	0.05	-0.001	-0.003	0.002	0.09	0.07	0.03	-0.001
R^2 = 0.21	SE	19.6	0.11	0.001	0.001	0.05	0.04	0.02	0.04	0.000
N = 117	tValue	1.52	0.44	-0.92	-2.40	0.04	2.02	2.97	0.74	-1.72
	Pr>|t|	0.13	0.66	0.36	0.018	0.97	0.045	0.004	0.46	0.089

*) PE = Parameter Estimate;
SE=Standard Error

5.3.4 Annual variations in N, P and K uptakes in aboveground biomass

Uptake of N in aboveground biomass ranged from 100 to 190 kg ha^{-1}, with uptake in wet years nearly twice as high as those in dry years. Uptake of N was related to added fertilizer and stover, but not to added manure, and SWS and rainfall in July and August-October (Table 5.3). Splitting the data set in dry and wet years (see above) resulted in a higher percentage variance accounted for, and gave statistically significant effects of added stover and manure in dry years, but not in wet years (not shown). In addition, there was a statistically significant interaction between added NP fertilizer and manure in dry years but not in wet years.

Uptake of P in aboveground biomass ranged from 8 to 32 kg ha^{-1}, with the highest values in wet years. Uptake of P was related to added fertilizer and stover, but not to added manure, and SWS and rainfall in April-June, July and August-October (Table 5.3). Again, splitting the data set in dry and wet years resulted in a higher percentage variance accounted for, and gave statistically significant effects of added stover and manure in dry years, but not in wet years (not shown). In addition, there was a statistically significant interaction between added NP fertilizer and manure in dry years but not in wet years.

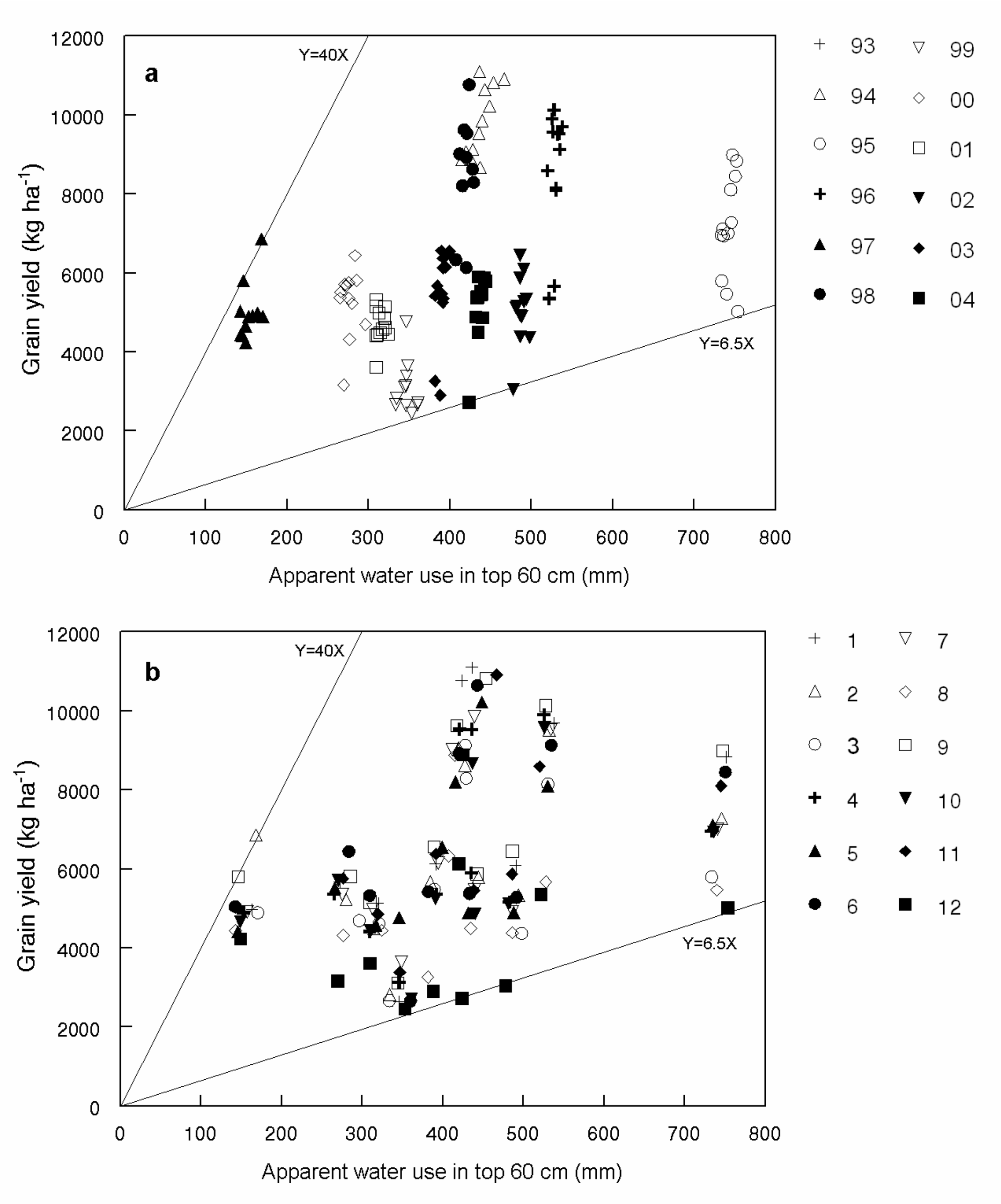

Fig. 5.5 Relationships between grain yield and apparent water use for all experimental years (upper panel) and treatments (lower panel). The lines Y=6.5X and Y=40X indicate extreme low and high water use efficiency, respectively, and are meant for comparison.

Uptake of K in aboveground biomass ranged from 50 to 90 kg ha^{-1}, and was statistically significant related to added fertilizer, stover and manure, and to rainfall in July (Table 5.3). The positive effects of manure and stover on K uptake, suggests indeed that stover and manure were important for supplying K to maize. Percentage variance accounted for was much higher for K uptake than for N and P uptake, but it should be noted that K uptake was not determined in 1993-1996. Splitting the dataset in dry and wet years did not increase the percentage variance accounted for.

Relationships between GY and N, P and K uptakes are shown in Figure 5.6. On average 40-50 kg of grain was produced per kg N taken up in aboveground biomass (range 24-80). Highest PhE was in the control treatment and in productive years 1994, 1996, 1998, 2003. For N, PhE (GY/Nuptake) was relatively low in 1999 (about 30 kg kg^{-1}). For P, PhE ranged from 160 kg in 1999 and 2004 to 800 kg in 2002. There were no clear patterns between treatments, indicating that climate had a much stronger effect than treatments on the PPhE (Figure 5.6). For K, PhE ranged from 44-60 kg in 1999 and 2004 to 120-150 kg in 2003. On average, treatment 2 (F=105, S=3000, M=0 kg ha^{-1}) had the highest KPhE, but patterns were not consistent over years. Also for K, climate had a stronger effect than treatments on PhE.

Ratios of P uptake to N uptake in aboveground biomass ranged from 0.06 to 0.3 (equivalent to N/P ratios of 4 to 16 (Figure 5.7)). Ratio of N/P was lowest in 2004 and highest in 2002. There were no clear and consistent patterns in N/P ratios between treatments. Ratios of K uptake to N uptake in aboveground biomass ranged from 0.3 to 1.0 (equivalent to N/K ratios of 1 to 3.6). Ratio of N/K was lowest in 2004 and highest in 2000. There were no clear and consistent patterns in N/K ratios between treatments (Figure 5.7).

Apparent N recovery Efficiency (NRE) was related to added fertilizer (linear and quadratic effects) and to rainfall in August to October, but the percentage variance accounted for was small (Table 5.3). The same holds for PRE. Mean NRE ranged from about 25% in the dry years 1997 and 1999 to 70-80% in the wet years 1996 and 1998. Mean PRE ranged from about 15% in the dry years 1997 and 1999 to 30-40% in the wet year 1996 and 1998. Splitting the data set in dry and wet years (see above) resulted in a much higher percentage variance accounted for, and showed statistically significant effects of fertilizer and manure in dry years, and of fertilizer and stover in wet years (not shown). Also, there were statistically significant effects of fertilizer and manure on PRE in both dry and wet years. In addition, there was a statistically significant interaction between NP fertilizer and manure in both dry and wet years (not shown).

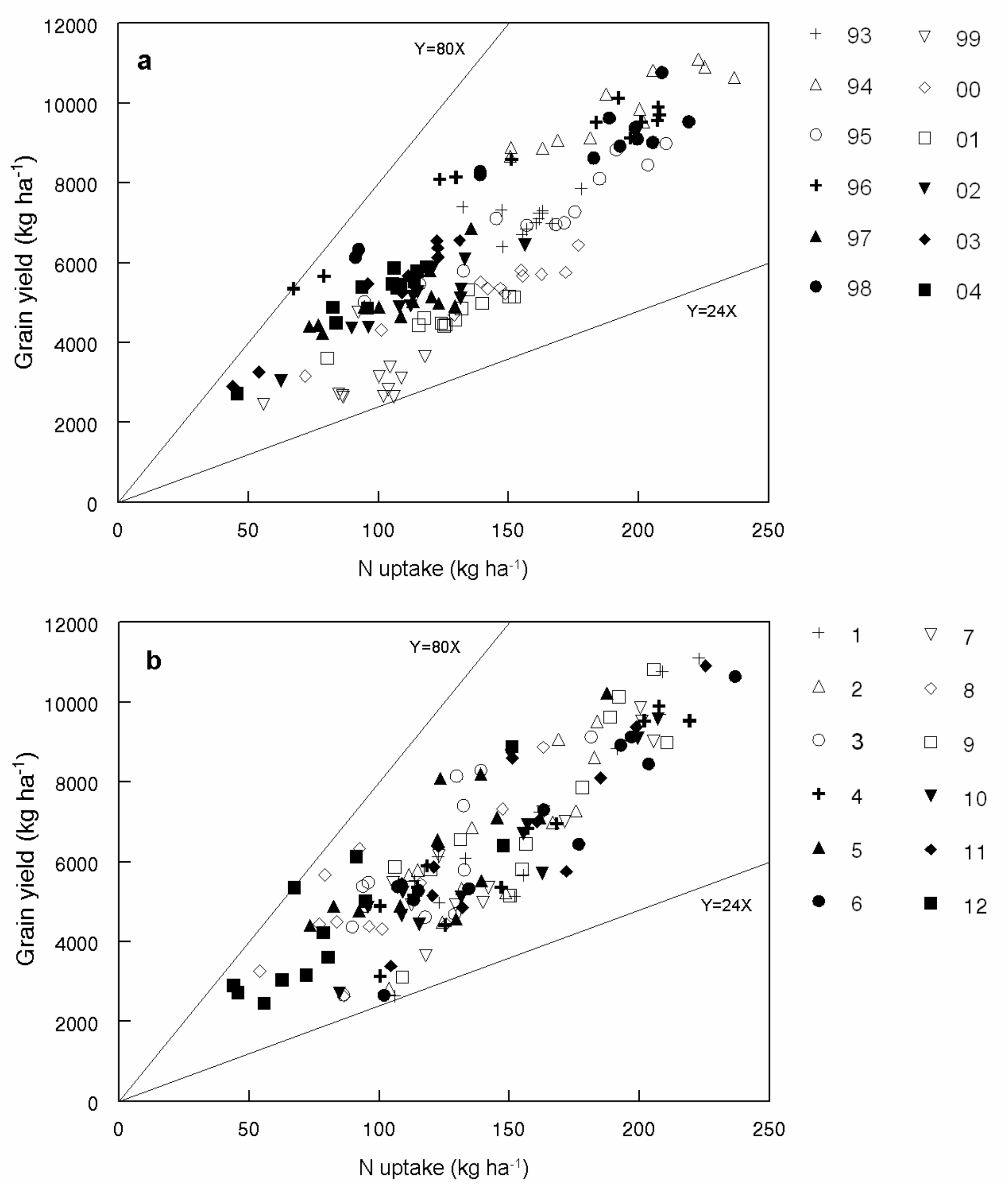

Fig. 5.6 Relationships between grain yield and N, P and K uptake for all experimental years (a, c and e) and treatments (b, d and f). The two lines within each graph approximate maximum dilution (high physiological nutrient use efficiency (PhE); upper lines) and maximum accumulation (low physiological nutrient use efficiency; lower lines).

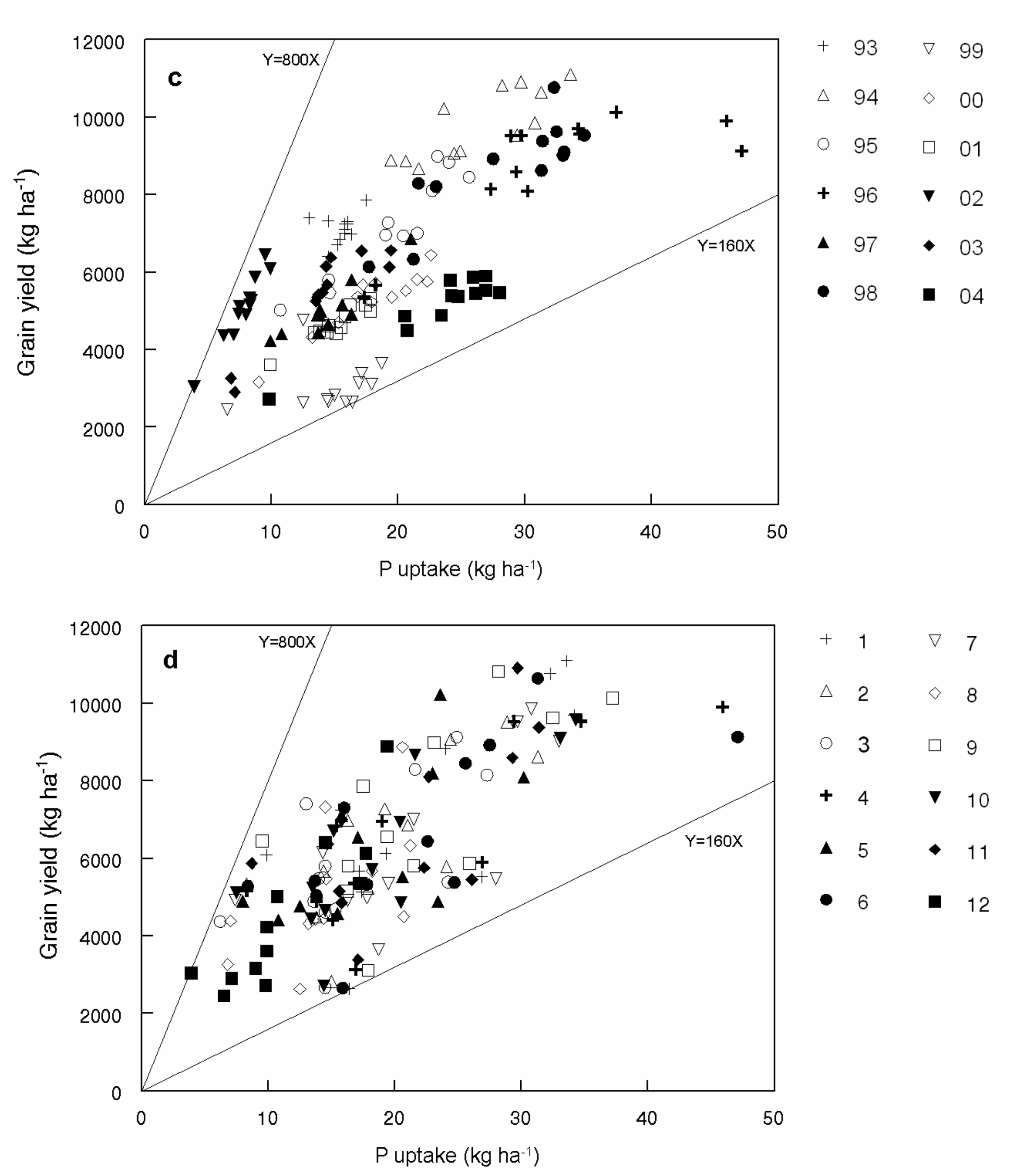

Fig. 5.6 Relationships between grain yield and N, P and K uptake for all experimental years (a, c and e) and treatments (b, d and f). The two lines within each graph approximate maximum dilution (high physiological nutrient use efficiency (PhE); upper lines) and maximum accumulation (low physiological nutrient use efficiency; lower lines).

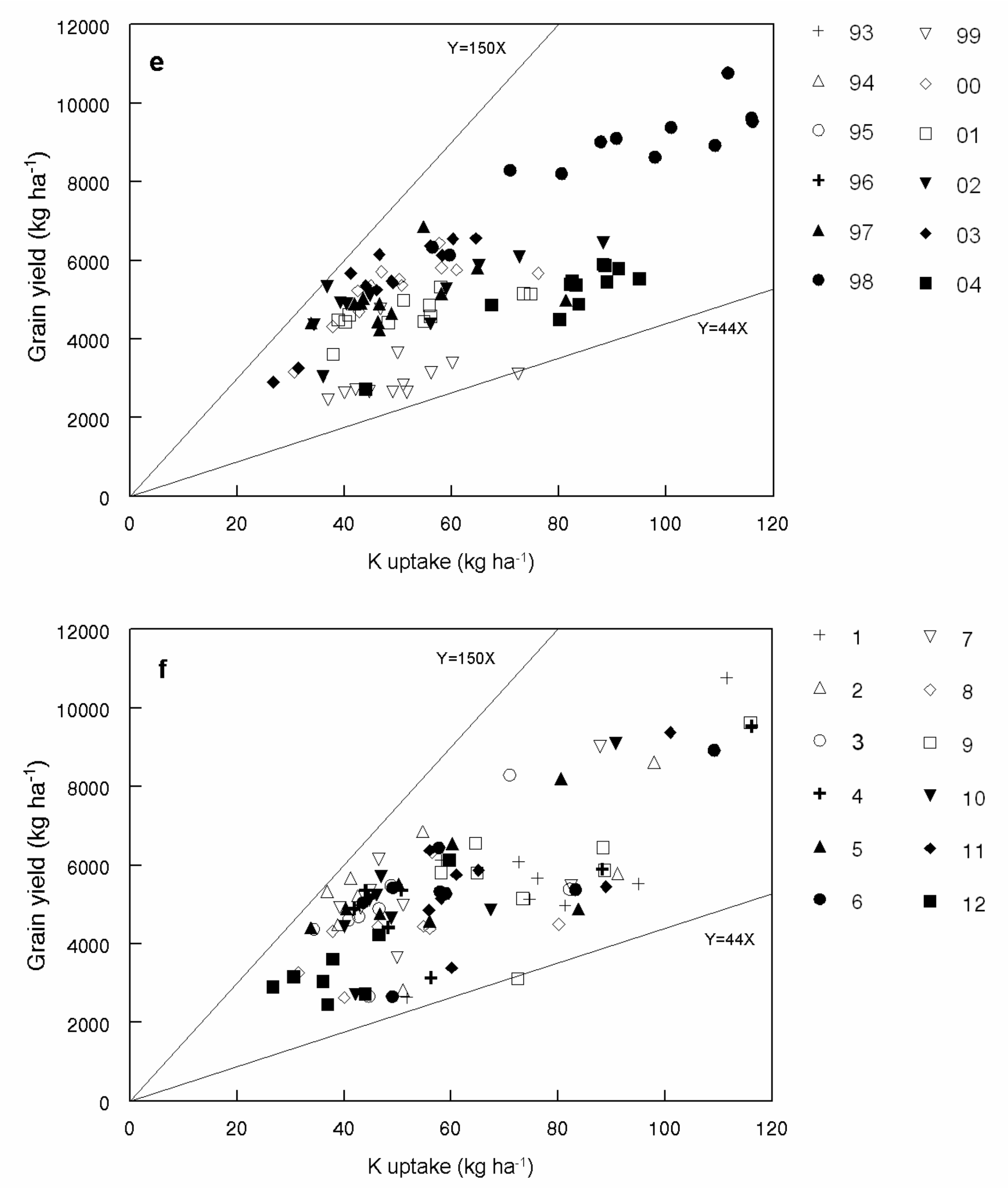

Fig. 5.6 Relationships between grain yield and N, P and K uptake for all experimental years (a, c and e) and treatments (b, d and f). The two lines within each graph approximate maximum dilution (high physiological nutrient use efficiency (PhE); upper lines) and maximum accumulation (low physiological nutrient use efficiency; lower lines).

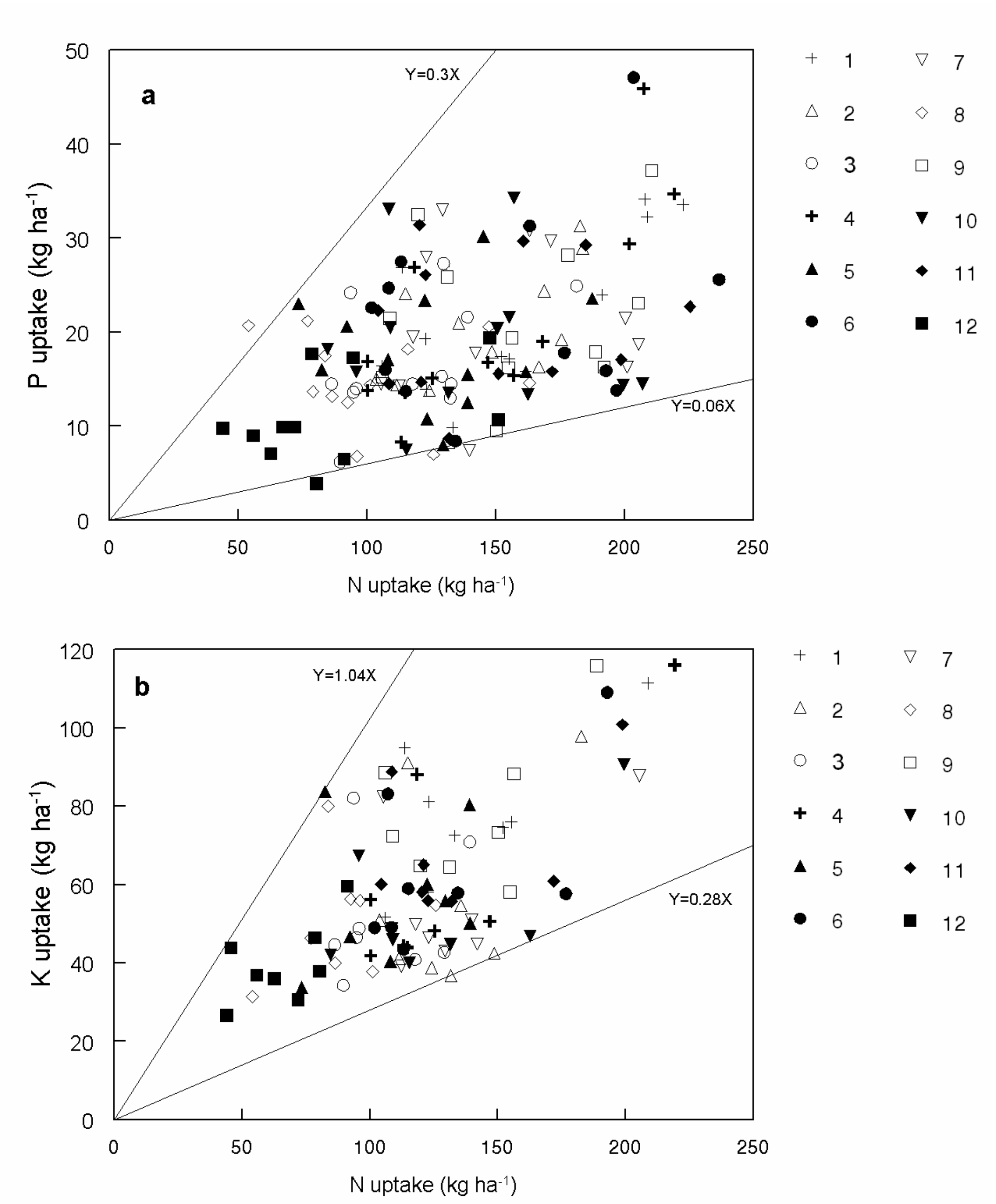

Fig. 5.7 Relationships between P uptake and N uptake (a) and between K uptake and N uptake (b) for all treatments. The lines within the graphs indicate extreme high (upper lines) and extreme low (lower lines) ratios of P:N (a) and K:N (b) in the aboveground biomass at harvest.

5.4 Discussion and conclusions

Grain yields of spring maize in drylands of northern China were greatly influenced by SWS and GSR. Differences between years in mean GY were in the order of 200 to 300% (e.g. between 1994 and 2004), and these differences were mainly related to SWS and GSR. In addition, GY was limited by the availability of nutrients, especially N, but likely also P and K. Added NP fertilizer, maize stover and cattle manure increased GY and N, P and K uptake in aboveground biomass, but effects of maize stover and cattle manure were not statistically significant in all years. Balanced combination of NP fertilizer, maize stover and cattle manure gave the highest yield. Averaged over the 12 year experimental period, a balanced combination of NP fertilizer, maize stover and cattle manure (treatment 9) increased GY by 60% relative to the control treatment. Clearly, fertilization effects were smaller than rainfall effects.

The difference in GY between the control treatment and the treatments with balanced combinations of NP fertilizer, stover and manure tended to increase over time, mainly because GY of the control treatment declined during the experimental period, due to nutrient depletion of the soil. Yields of other treatments also tended to decline during the experimental period, but this decline could be ascribed to changes in the amounts and distribution of rainfall over the growing season (Table 5.3, Figure 5.4). Grain yields in some years may also have been affected by diseases (mainly head smut). Decreasing GSR, soil nutrient depletion and diseases have been identified as major causes for declining yields of continuous spring maize cropping systems in northern China (Cao et al., 2001), Wang et al., (2002), Zhao et al. (2002), Li et al. (2003), Jin et al. (2004), Li (2004), and Bai et al.(2006).

5.4.1 Water limited grain production

Water use efficiency (WUE) averaged over the 12-year period ranged from 1.1 for the control treatment to 1.9 kg ha^{-1} m^{-3} for treatments with balanced additions of NP fertilizer, stover and manure (Table 5.2). These values are common for non-irrigated maize production and clearly show that balanced fertilization increases the efficiency of water use (Viets, 1962; Van Keulen and van Laar, 1986; Van Keulen and Seligman, 1987; Huang et al., 2003; Fan et al., 2005a). Differences in WUE were much larger between years than between treatments (Figure 5.4). Even at similar apparent water use, there were large differences in GY and hence in WUE. Some of these differences may be attributed to differences in maize variety, as different varieties were used for the periods 1993-1997, 1998 and 1999-2004. A major factor explaining differences in mean WUE between years is the distribution of the rainfall over the growing season. Our results indicate that the amount of soil water at seeding (SWS) and the amount of rainfall during tasseling, commonly in July, are highly critical (Table 5.3). A third possible factor explaining differences in mean WUE between years is related to N losses and low N use efficiency. For example, the low WUE in 2004 (Figure 5.5) is accompanied by low N/P and low N/K ratios (Figure 5.7) and relatively high N use efficiency (Figure 5.6). This may suggest that N uptake was low because soil N was lost prior to or during the growing season. Alternatively, diseases may have (also) played a role. We recall that NP fertilizer, stover and manure were applied in autumn; late season rainfall and rainfall in winter and spring may have contributed to N losses via leaching and denitrification (Mosier et al, 2004; Cai et al., 2002). Evidently, high SWS is beneficial from the viewpoint of germination and early growth of maize (Cai et al., 1994), but on the other hand may also contribute to N losses and low N use efficiency and thereby to low WUE.

5.4.2 Nutrient limited grain production

Balanced combinations of NP fertilizer, stover and manure gave higher GY than additions of NP fertilizer alone, at all levels of NP (Table 5.2; Figure 5.3), suggesting that the effects of manure and especially stover were additional to the effects of NP fertilizer. Results presented in Table 5.3 and Figures 5.3 and 5.6 show that stover and manure increased K uptake. Treatments with relatively large applications of NP fertilizers and low application rates of stover and manure had relatively high N/K ratio in the aboveground biomass (Figure 5.6), indicating unbalanced supply of N and K. Deficiency of K was not foreseen at the start of the experiment in 1993, and analyses of K in biomass only started in 1997. Our results suggest that 'the stover effect' likely was a 'K effect'. Deficiency of K in crop production usually appears following increases in NP fertilizer applications and decreases in the use of organic fertilizers (Lin et al., 1999; Ju et al., 2005). Intensification of crop production, in combination with unbalanced fertilization, has already resulted in depletion of potassium (K) in soils over large areas in China (Jin et al. 1999), India (Hasan, 2002) and other countries in South-East Asia (Dobermann et al., 1996, 1998; Ladha et al., 2003; Hoa et al., 2003)

Maize GY responded to N and K applications and possibly also to P application. However, the effects of N and P were confounded because N and P applications were combined in all treatments. The response to N also follows from the relatively high PhE for N in the control treatment, which ranged from 40 to 80 kg grain per kg N taken up (Figure 5.6). The higher value is close to 'maximum dilution', which is indicative for shortage of N (Janssen et al., 1990; Janssen and de Willigen, 2006a). For K, PhE in the control treatment ranged from 40 to 120 kg grain per kg N taken up, and for K, PhE ranged from 160 and 800 kg grain per kg P taken up (Figure 5.6). Such wide ranges reflect variations between maximum dilution and maximum accumulation of K and P in the aboveground biomass (Janssen et al., 1990). The annual variations in PhE for P and K were related to the distribution of rainfall over the growing season. For both P and K, differences in PhE were smaller between treatments than between annual means, suggesting that GSR had much stronger effects on the K and P use efficiencies than NP fertilizer, stover and manure.

Fertilizers, stover and manure were applied in autumn after harvest of the crop, just before ploughing, and about 6 months before seeding. This practice was adopted to reduce wind erosion and soil drying in spring and also to minimize labor requirement (Cai et al., 2001; Wang et al., 2006). The trade-off is that added nutrients are stored in the soil for a long time and made conducive for losses. Mean apparent N recoveries (NRE) were in the range of 30 to 55%, which are common values for rainfed maize (Balashubramanian et al., 2004; Krupnik et al., 2004), suggesting indeed that N losses were not excessive. In years with a favorable rainfall distribution, NRE ranged from 50 to 90%. However, NRE values in treatments with stover and manure were positively affected by addition of K, especially during the second half of the experimental period when GY and N uptake of the control treatment had declined to relatively low values. We conclude that adding stover and manure in autumn just before ploughing, combined with direct drilling of maize seeds in spring, is a proper way of minimizing wind erosion and labour requirement, while crop yield and N use efficiency can still be relatively high. The experiment does not allow making a conclusion about the possible superiority of reduced tillage over conventional tillage practices as regards GY and nutrient use efficiencies.

Interactions between NP fertilizer, stover and rainfall in some years may point at temporary immobilization of N during the decomposition of stover, which has a high C/N ratio. Adding stover and N fertilizer simultaneously may temporary lock up mineral N in soil organic matter and thereby circumvent its possible loss from soil by leaching and denitrification, and its uptake by plant roots. This temporary immobilization of N in autumn and its partial mineralization during the growing season may have contributed to positive effects of stover application and also to the positive effects of combined applications of N fertilizer, stover and manure (Kramer et al., 2002). Pattey et al (2001) recommended split applications of N fertilizer, with about half or two-thirds of the recommended N dose at sowing and the supplement after emergence of the crop. Supplemental N should depend on rainfall conditions and the N status of the soil or crop (Schröder et al., 2000). In dry years, supplemental N should not be applied in any tillage system (Anga´s et al., 2005). Split application increases labor requirement but usually increases N use efficiency. Under the conditions of Shouyang, total N dressing should be in the range of 100-150 kg ha^{-1} yr^{-1}, depending on the application of stover and manure. When split applied, the first N dressing (up to 100 kg ha^{-1}) should be applied at seeding, depending also on SWS and soil mineral N, and a possible second N dressing (up to 50 kg ha^{-1}) at the 4-6 leaf stage, depending on early season rainfall and the N status of the soil (Schröder et al., 2000; Dobermann and Cassman, 2002). The feasibility of such split application technology in practice needs to be tested further.

5.4.3 Conclusions

Traditional Chinese farming was based on efficient utilization and recycling of natural resources. The increasing quest for food by the growing human population led to an increase of N (and P) fertilizer use, unbalanced nutrition and decreasing resource use efficiency. The results of this long-term field experiment show that modest applications of stover and manure can contribute to increase the use efficiency of N fertilizer.

Grain yield and N, P and K use efficiencies of rainfed maize were strongly related to rainfall and to soil water at seeding. The huge annual variations in physiological N, P and K use efficiencies indicate that there is scope for improvement of fertilizer use efficiency by split application.

The design of this field experiment was meant to provide the most effective and efficient way to balanced fertilization. There were three nutrient resources (NP fertilizer, stover and manure), each applied at five rates, and these were combined in an incomplete factorial design of 12 treatments only. The statistical model pertinent to the design was able to describe the mean responses of NP fertilizer, stover and manure reasonably well, but could not explain the strong interactions between GSR and the effects of NP fertilizer, stover and manure. Evidently, nutrient management under rainfed conditions requires rainfall to be taken into account in a dynamic approach (see also chapter 6). The feasibility and adoptability by farmers of split applications of N fertilizer combined with soil and/or plant analyses should be tested in practice.

6 Long-Term effects of crop residue, manure and fertilizer on dryland maize under reduced tillage in northern China: II Nutrient balances and soil fertility

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Manuscript

Summary

A long-term experiment was carried out in the dryland of northern China to assess the effects of applications of maize stover, cattle manure and NP (1:0.44) fertilizer on partial nitrogen (N), phosphorus (P) and potassium (K) balances, extractable soil N, P and K, and soil organic matter in a spring maize cropping system, under reduced tillage conditions. The experiment was set-up according to an incomplete, optimal design, with 3 factors and 12 treatments (including a control) in duplicate.

Statistical analyses using multiple regression models showed that the partial N, P and K balances were strongly influenced by annual variations in the amounts of soil water at seeding (SWS) and growing season rainfall (GSR). Most treatments had positive P but negative N and K balances. Cumulative P and K balances were reflected in extractable soil P (P-Olsen) and K (exchangeable K), but the weak relationships indicate that the sorption of P and buffering of K were strong. Cumulative balances of effective organic carbon (C) were weakly related to soil organic C (SOC) contents after 12 years. Negative C balances were related to decreases in SOC, but positive C balances were not translated in increases in SOC.

The analysis of nutrient balances and soil fertility indices revealed that nutrient inputs in most treatments were far from balanced. It is concluded that the concepts of 'ideal soil fertility level' and 'response nutrient management' provide practical guidelines for improving nutrient management under the variable rainfall conditions of dry land areas.

Keywords: maize, crop residue, dryland, fertilizer, manure, nutrient balances, soil organic carbon, soil fertility

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6.1 Introduction

China has a long tradition of efficient recycling of organic residues in agriculture, but this tradition is rapidly disappearing following the intensification of agricultural production, the increased use of mineral fertilizers and the increasing urbanization and decoupling of crop production and animal production (Ju et al., 2005; Yang, 2006). The intensification of agricultural production has greatly increased the volume of agricultural production, but at the same time has contributed to a decrease in resource use efficiency, land degradation through increased wind and water erosion, and to pollution of groundwater and surface waters (Zhang et al., 2005; Rozella et al., 1997; Liu and Diamond, 2005; Liu, 2005). Evidently, China is at a crossroads of its agricultural, industrial and environmental developments. It faces the challenges of drastically increasing resource utilization through combining insights and practices from history with the current reality. Both short-term remedies and longer-term adjustments are needed for sustaining food and feed production while safeguarding the natural environment ((Rosegrant and Cai, 2001; Zhang et al., 2005)

The dryland farming regions of northern China provide food to a large fraction of the increasing Chinese population. This area is vulnerable to wind and water erosion, and to environmental degradation due to its inherent soil and climatic characteristics (Wang et al., 2006a, 2006b), and the current management practices. Continuous maize (*Zea mays* L.) or wheat (*Triticum aestivum* L.), and wheat-maize rotations are the dominant cropping systems. The current practice in dryland areas in northern China is to remove crop residues from the field after harvest to feed animals or to use it as biofuel, with little or no return of manure and ashes to the fields where the crop residues came from. Burning crop residues in the field is also a common practice in some areas. After harvest, the soil is ploughed and ploughed once again in spring before seeding. These practices contribute to decreasing soil organic carbon (SOC) contents (Yang, 1996) and to soil drying and severe wind erosion in winter and early spring (Wang et al., 2006a). Further, recommendations for fertilizer applications are based on potential yields and do not make provision for differences in soil fertility and for other possible nutrient sources. In practice, the uniform ‘blanket’ fertilizer recommendations are often exceeded with as consequence low nutrient use efficiencies. Evidently, there is an increasing need to refocus current practices and recommendations so that multiple goals can be matched; i.e., sustained high crops yields, and efficient resource utilization.

In the current study, alternative nutrient management practices under reduced tillage were evaluated, to minimize soil drying and wind erosion in spring and at the same time to improve soil fertility and nutrient use efficiencies. Alternative practices included the incorporation in the soil of various mixtures of maize stover, manure and mineral fertilizer in fall and to seed in spring without prior soil cultivation. The effectiveness of these practices was assessed in a long-term field experiment in Shanxi province in northern China. The reduced tillage practice has been shown to be highly effective in decreasing wind erosion (Cai et al., 2003; Wang et al., 2006a). Effects of applying organic residues and mineral fertilizer in autumn on grain yields and nitrogen (N), phosphorus (P) and potassium (K) use efficiencies have been reported in Chapter 5. This paper discusses partial N, P and K balances, and the changes in soil organic matter and soil fertility indices for P and K.

Nutrient input-output balances of agroecosystems provide insight in the cycling and use efficiency of nutrients, and in possible nutrient losses from these systems to the wider environment (Goodlass et al., 2003; Oborn et al., 2003; Zebarth et al., 1999) Positive balances are expected to result ultimately in environmental pollution and negative balances in soil depletion and ultimately to loss of productivity. However, the impact of a balance cannot be seen independently from actual soil fertility. At low fertility levels, nutrient balances should be positive to build up soil fertility till the target level, while at high fertility levels balances should be negative to avoid environmental pollution (Janssen and de Willigen, 2006a; 2006b). Hence, nutrient balances should be evaluated concomitant with assessing soil fertility, and vice versa.

6.2 Materials and Methods

6.2.1 Site description

The ongoing long-term field experiment started in 1992 at the Dryland Farming Experimental Station in Shouyang, Shanxi province (112°-113°E, 37°-38°N) in northern China. The area has a mean altitude of 1100 m above sea level and a continental monsoon climate with an average annual rainfall of 520 mm. Severe erosion in the past has led to the formation of a hilly landscape. The dominant cropping system is continuous spring maize, which accounts for over 50% of the total area for crop production. The study area is representative of a typical farming region dependent on rainfall. Spring drought often is a limiting factor for seed germination and the emergence and growth of spring maize. The experimental site has a sandy loam cinnamon soil, classified as Calcaric-Fluvic Cambisols (ISS-CAS, 2003; IUSS, 2006). At the start in 1992, soil pH was 7.9, and SOC and SON contents were 15 and 1.0 g kg^{-1}, respectively. Available soil P and soil K in the top 20 cm soil were low to medium, judged on the basis of P-Olsen (7.3 mg kg^{-1}) and NH_4OAc extractable K (2.2 mmol kg^{-1}).

6.2.2 Experimental design

The experiment was set-up according to an incomplete, optimal design (Xu, 1988) with 3 factors (NP fertilizer, maize stover and cattle manure), and 12 treatments, including a control treatment, in duplicate. Fertilizer NP (ratio $N:P_2O_5$ = 1:1) applications were 0, 31, 105, 179 and 210 kg ha^{-1}. Maize stover applications were 0, 879, 3000, 5121 and 6000 kg ha^{-1}. Cattle manure applications were 0, 1500, 3000, 4500 and 6000 kg ha^{-1} (see also Chapter 5).

6.2.3 Methods

6.2.3.1 Field experiment and sample measurement

Plots (6 x 6 m^2) were laid down randomly in duplicate. Locally recommended maize varieties were used, i.e., Yandan No.12 in 1993-1997, Shandannong No.1 in 1998, and Jindan No.34 in 1999-2004. The N and P fertilizers were urea (46% N) and superphosphate (16% P_2O_5) in a ratio of N to P_2O_5 of 1:1. Maize stover and cattle manure were obtained from local farms. The weighed mean contents of organic matter, total N, total P (as P_2O_5) and total K were 75%, 0.63%, 0.09% and 0.72% for maize stover (ratio of N:P:K=100:6:114) and 36%, 0.96%, 0.39% and 0.74% for cattle manure (ratio of N:P:K=100:18:77), respectively. Maize stover, cattle manure and fertilizers were broadcast and incorporated into the soil after maize harvest in the fall by ploughing (20 cm deep). Seeding was done in spring, usually at the end of April, without any tillage. Maize was seeded in rows at distances of 30 cm within the rows and 60 cm between rows (plant density 55555 ha^{-1}).. Weeding was done manually twice during the growing season. Maize was harvested close to the ground using sickles and all harvested biomass was removed from the plots, usually in October.

Grain yield and crop residues (rachis + stems + leaves + husks) were determined by harvesting the centre 1.8 x 2.1m^2 of the plots. Samples of grain and corn residues were oven dried at 70ºC to a uniform weight and then weighted. Harvest index (HI) was estimated as the ratio of grain to total aboveground biomass yield. Plant samples of grain and stover were analyzed for total N using the Kjeldahl method, total P using the H_2SO_4-$HClO_4$ method and total K using the HNO_3-$HClO_4$flame photometry methods, respectively (Westerman, 1990). Plant analyses of N and P started in 1993, that of K in 1997. Grain yields and N, P and K uptakes have been described in detail in Chapter 5.

Soil samples were taken at seeding to determine soil moisture at seeding (SWS), and after harvest to determine extractable N, P and K. Each sample was a composite of three random 2-cm diameter cores per plot, taken at depths of 0-20, 20-40, 40-60, 60-80, and 80-100 cm. Samples were analyzed for extractable soil N (SEN), using the alkali-hydrolytic diffusion method (Keeney and Nelson, 1982). Extractable soil P (SEP) was determined using Olsen's method, and extractable soil K (SEK) using 1 M NH_4OAc. Soil organic carbon (SOC) was determined in the 0-20 and 20-40 cm layers by wet oxidation (using H_2SO_4 - $K_2Cr_2O_7$).

6.2.3.2 Nutrient and carbon balance estimation

Partial N, P or K balances were estimated per treatment from measured N, P or K inputs and outputs, using the following equations (in kg ha^{-1}):

$$NPK_{inputs} = NP_{fertilizer} + NPK_{stover} + NPK_{manure} \quad [1]$$

$$NPK_{outputs} = NPK_{uptake\ in\ aboveground\ biomass}$$

$$NPK_{balance} = NPK_{inputs} - NPK_{outputs} \quad [2]$$

$NP_{fertilizer}$ is the added N and P via fertilizer, NPK_{stover} the added N, P and K via stover, NPK_{manure} the added N, P and K via manure, and $NPK_{uptake\ in\ aboveground\ biomass}$ the N, P and K taken up in the aboveground biomass of maize.

The soil C balance was estimated per treatment and year as follows:

$C_{input} = C_{stover} + C_{manure} + C_{stubble+roots}$

$C_{output} = k_{stover} * C_{stover} + k_{manure} * C_{manure} + k_{stubble+roots} * C_{stubble+roots} + k_{SOM} * C_{SOM}$

$C_{balance} = C_{input} – C_{output}$

Where

C_{stover} = the input of C via added stover, kg ha^{-1};

C_{manure} = the input of C via added manure, kg ha^{-1};

$C_{stubble+roots}$ = the input of C via stubble and roots left on the field after harvest, estimated at 20% of aboveground biomass at harvest (Zhang et al., 1984), kg ha^{-1};

C_{SOM} = the amount of soil C (0-20 cm) after harvest, using a bulk density of 1.2 Mg m^{-3}

k_{stover} = decay constant of added stover in the first year, dimensionless

k_{manure} = decay constant of added manure in the first year, dimensionless;

$k_{stubble+roots}$ = decay constant of stubble and roots during the first year, dimensionless;

k_{SOM} = decay constant of soil organic matter, dimensionless.

Decay constants were taken from literature (Table 6.1). Because of the uncertainty in the actual decay constants, simple sensitivity analyses were carried by varying the k values in the balance equations.

Table 6.1 Decay coefficients for stover, manure, stubble + roots and soil organic matter (SOM) in the calculation of C balances. Three sets of literature values have been used.

Stover	Manure	Stubble+ roots	SOM	Literature
0.6	0.8	0.6	0.02	Janssen, 1992
0.67	0.56	0.55	0.02	Yang, 1996
0.8	0.48	0.55	0.0285	Cai, 1996

6.2.3.3 Data statistics

Multivariate statistical analysis were carried to examine relationships between N, P and K balances and added NP fertilizer, stover and manure, growing season rainfall (GSR) and soil water at seeding (SWS). Extractable soil N (SEN), P and K (SEP and SEK) were also related to added NP fertilizer, stover and manure, GSR and SWS, using GLM, and REG procedures of the SAS Institute, Inc. (2004).

6.3 Results

6.3.1 Partial N, P, K and C balances

Mean N balances ranged from -84 kg ha^{-1} yr^{-1} for the control treatment to 90 to 99 kg ha^{-1} yr^{-1} for treatments with high NP fertilizer application rates (Table 6.2). Approximately half of the treatments had a negative partial N balance. At modest application rates of NP fertilizer, stover and manure in treatment 11 (F=105, S=3000, M=3000), N inputs equaled N outputs. However, these partial balances do not account for N inputs via atmospheric deposition (approximately 10 kg ha^{-1} yr^{-1}; Duan et al., 2001) and net mineralization of soil organic matter, and they do not account for possible N losses via erosion, ammonia volatilization, denitrification and leaching. Yet, mean N surpluses were significantly related to extractable soil N (SEN) after harvest (R^2 = 0.63).

Mean P balances ranged from -12 kg ha^{-1} yr^{-1} for the control treatment to 74 kg ha^{-1} yr^{-1} for treatment 7 with the highest NP fertilizer application rate (Table 6.2). Most treatments had a highly positive P balance. Only the two treatments (treatments 8 and 12) that did not receive NP fertilizer had a negative P balance. The results indicate that applications exceeding 31 kg P_2O_5 fertilizer (equivalent to 13.5 kg P) led to a mean P surplus. Surpluses of P were linearly related to mean extractable soil P (SEP, or Olsen P) (R^2 = 0.85).

Mean K balances ranged from -43 kg to 12 kg ha^{-1} yr^{-1} (Table 6.2). Most treatments had a negative K balance, including the treatment with the highest mean grain yield (treatment 9). Only treatments with relatively large inputs of stover and manure, combined with sub-optimal or above-optimal N fertilizer inputs (treatments 5 and 6), had a slightly positive K balance. The negative K balances suggest that the soil K pool was depleted, but K balances were poorly related to mean exchangeable soil K (R^2 = 0.21).

Calculated mean C balances ranged from -600 to 900 kg ha^{-1} yr^{-1} (Table 6.2). Balances were negative for treatments with relative low inputs of stover and manure. Balances were highly sensitive to the choice of the decay coefficients, especially to k_{stover} and k_{SOM}. The significant differences between treatments in C balances led to slight but significant differences in mean SOM levels; the treatment with the lowest mean C balance had the lowest mean SOM content. The linear correlation coefficient (R^2) for the relationship between the mean C balance and the overall mean SOM was 0.4. Using a decay coefficient for SOM of 0.0285, as derived for Shouyang by Cai et al., (1996) gave lower cumulative C balances than using the mean value for northern China (0.02) estimated by Yang (1996). Cumulative C balances over the 12-year experimental period ranged from -7,500 to 4,700 kg ha^{-1} when using Cai's coefficients and from -4,000 to 11,000 kg ha^{-1} when using Yang's coefficients. This indicates that maximal differences between treatments in input of effective C were in the range of 12,200 to 15,000 kg ha^{-1} over the whole experimental period.

Table 6.2 Effects of NP fertilizer (F), maize stover (S) and manure (M) in various combinations on mean grain yield (GY), mean partial N, P, K and C balances, and mean extractable soil N (SEN), P (SEP) and K (SEK) at harvest time in the top 20 cm layers per treatment for the whole experimental period (1993-2004). For the calculation of C balances, use was made of decay coefficients from (a) Janssen, (1992), (b) Yang, 1996, and (c) Cai (1996). Note, treatments are arranged in the order of increasing grain yields. (see text).

Treatment	Added F, S and M, respectively, (kg ha^{-1})			GY* (kg ha^{-1})		N balance (kg ha^{-1})		P balance (kg ha^{-1})		K balance (kg ha^{-1})	
12	0	0	0	4587	E	-84	H	-12	G	-40	F
8	0	3000	1500	5139	D	-69	G	-11	G	-18	BCD
3	31	879	4500	5805	C	-40	F	4	F	-13	B
10	105	0	1500	6269	BC	-26	E	29	DE	-43	F
4	179	879	4500	6420	B	79	B	65	B	-21	BCD
5	31	5121	4500	6433	B	-21	E	4	F	12	A
7	210	3000	1500	6512	B	90	AB	74	A	-24	CD
2	105	3000	0	6528	B	-24	E	27	E	-35	EF
6	179	5121	4500	6668	AB	99	A	65	B	6	A
11	105	3000	3000	6740	AB	0	D	31	D	-26	DE
1	105	3000	6000	7114	A	20	C	34	C	-15	BC
9	105	6000	1500	7184	A	-3	D	28	E	-25	CD

Treatment	Cbalance (a) (kg ha^{-1})		C balance (b) (kg ha^{-1})		C balance (c) (kg ha^{-1})		SEN (mg kg^{-1})		SEP (mg kg^{-1})		SEK (mg kg^{-1})		SOM (mg kg^{-1})	
12	-370	I	-330	H	-622	H	64	D	7	F	93	C	24.7	D
8	215	F	244	F	-211	F	71	CD	16	E	104	BC	26.3	AB
3	53	G	303	E	36	D	75	ABC	17	DE	98	BC	24.8	BCD
10	-222	H	-94	G	-366	G	73	BC	26	BC	98	BC	25.1	ABCD
4	65	G	320	E	45	D	82	A	32	AB	99	BC	25.5	ABCD
5	775	B	899	AB	375	B	81	A	18	DE	105	BC	26.2	ABC
7	310	E	349	E	-99	E	80	AB	36	A	101	BC	25.6	ABCD
2	272	E	236	F	-227	F	72	CD	23	CD	98	BC	24.8	CD
6	794	B	922	A	394	AB	82	A	36	A	107	BC	26.5	A
11	402	D	520	D	99	D	76	ABC	32	AB	104	BC	25.5	ABCD
1	545	C	817	C	444	A	83	A	31	AB	121	A	25.7	ABCD
9	900	A	856	BC	240	C	79	ABC	22	CDE	108	B	25.4	ABCD

note: values with the same letter within a column are not significantly different at 5% level
* From: Chapter 5

6.3.2. Balances of NPK and C per treatment and year

Annual variations in partial N, P and K balances per treatment are shown in Figure 6.1. Variations between years increased in the order: P balances < K balances < N balances. Annual variations within treatments were up to 100 kg for N balances, 50 kg for K balances and up to 20 kg ha^{-1} for P balances. With time, N balances tented to become less negative (when negative) or more positive (when positive), because grain yields and N uptake tended to decrease over time (Chapter 5). This decreasing trend was most clear in treatments receiving little or no NP fertilizer (treatments 8, 12 and 3).

Variations in N, P and K balances were related to added fertilizer, stover (except for P balances) and manure, and to soil water at seeding (SWS) and growing season rainfall (GSR), except for K balances (Table 6.3). The negative regression coefficients for SWS and GSR reflect increased NPK uptakes and hence less positive balances during wet years compared to dry years. Potassium balances were not related to SWS and GSR, possibly because K balances were established only from 1997 onwards and because variations in SWS and GSR were relatively small during the period 1997-2004 (Chapter 5).

Annual variations in balances of effective C were relatively small, with maximal differences between years within treatments of 500 kg ha^{-1} yr^{-1}, nearly independent of the choice of decay coefficient for SOM (Figure 6.2). Variations in C balance were related to added fertilizer, stover and manure, and to SWS but not to GSR (Table 6.3). The positive regression coefficients for SWS reflect increased stover and stubble production in wet spring (years). Opposite to the N balances, C balances tended to become less positive (or more negative), because yield of aboveground biomass tended to decrease over time, as a result of decreasing yields (Chapter 5).

6.3.3 Extractable soil N and total soil organic C per treatment and year

Extractable soil N (SEN) at harvest was relatively high, with values ranging from 30 to 120 mg kg^{-1} in the top 20 cm (Figure 6.3). With depth, SEN tended to decrease, except for treatments receiving N fertilizer at rates ≥105 kg ha^{-1} yr^{-1}. Also in the control treatment (treatment 12), SEN was relatively high with values ranging from 30 to 90 mg kg^{-1} in the topsoil and from 20 to 60 mg kg^{-1} in the subsoil, while maize suffered from N shortage in most years (Chapter 5). These relatively high values suggest that not all extractable N, determined using the alkali-hydrolytic diffusion method, was plant available N. The relatively high SEN values are probably related to the decomposition of labile organic N compounds such as glucosamine during the extraction, as discussed by Keeny and Nelson (1982). The alkali-hydrolytic diffusion method is still widely used in China, because of its low costs and simplicity, but the major soil laboratories have deleted this method because of its potential of overestimating soil mineral N (Dr. Ju Xiaotang, 2006, personal communication). Here, SEN values will be discussed only to compare treatments in a relative sense.

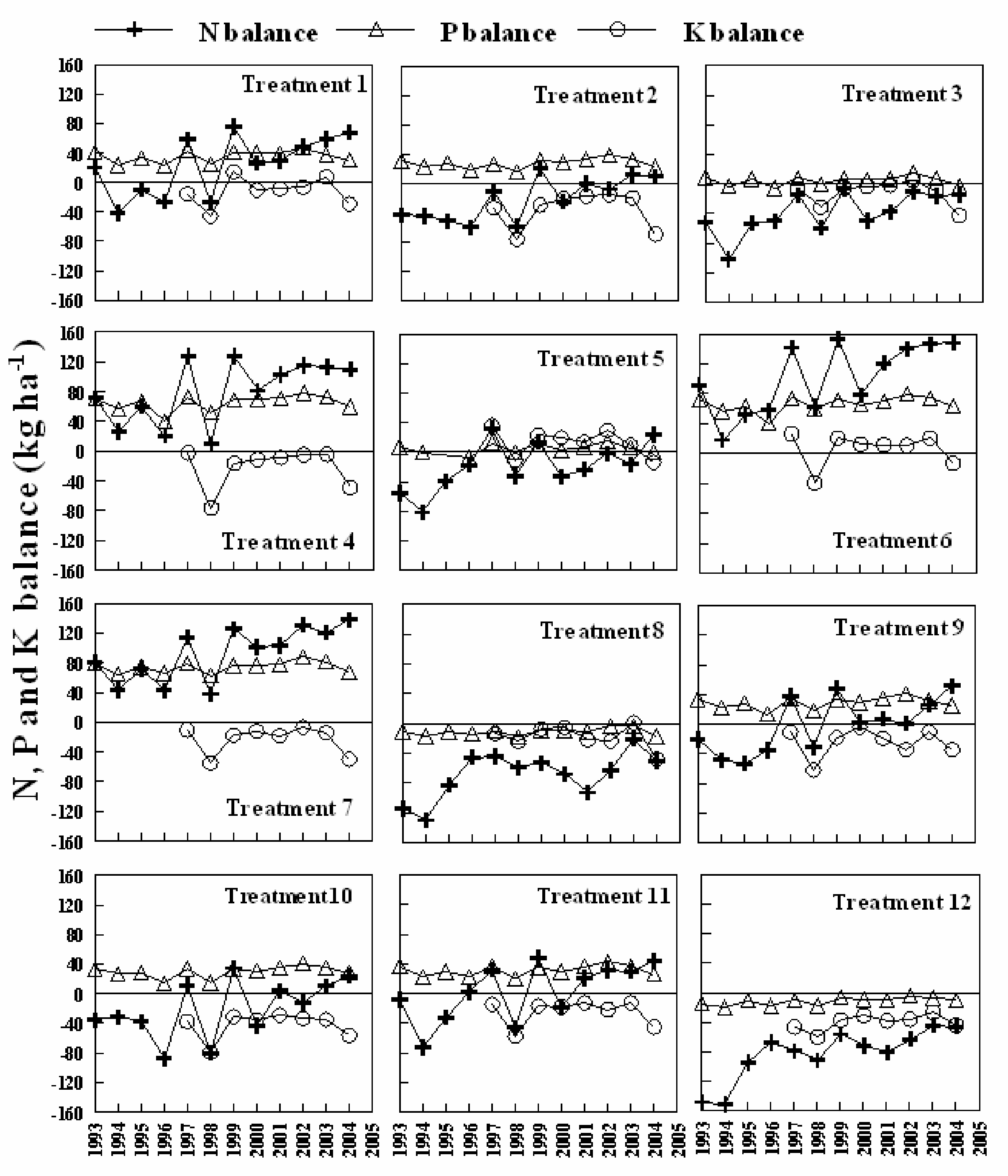


Fig. 6.1 Partial N, P and K balances per treatment during the experimental period 1993 - 2004. Lines between dots are shown for reasons of clarity; they do not have other meanings. Note that K balances only started in 1997.

Table 6.3 Coefficients of the regression models for partial N, P and K balances (in kg ha^{-1}), and extractable soil N (SEN), P (SEP) and K (SEK) (in mg kg^{-1}). The dependent variables were added NP fertilizer, stover and manure, growing season rainfall (GSR) and soil water at sowing (SWS). For fertilizer (Fsq) and GSR (GSRsq) also quadratic relationships were examined.

Dependent Variable		Intercept (b0)	Fertilizer (b1)	Stover (b2)	Manure (b3)	GSR (b4)	SWS (b5)	Fsq (b11)	GSRsq (b44)
N balance	**PE**	13.5	0.21	0.004	0.01	-0.13	-0.15	0.003	0.000
R^2 = 0.74 , n = 128	**SE**	35.1	0.15	0.002	0.00	0.09	0.07	0.001	0.000
	tValue	0.39	1.40	2.22	4.97	-1.43	-2.21	3.57	0.43
	Pr>|t|	**0.70**	**0.16**	**0.03**	**<.0001**	**0.16**	**0.03**	**0.001**	**0.67**
P balance	**PE**	26.1	0.34	0.000	0.001	-0.07	-0.06	0.000	0.000
R^2 =0.94, n = 127	**SE**	7.07	0.03	0.000	0.000	0.02	0.01	0.000	0.000
	tValue	3.70	11.1	-0.19	3.95	-3.82	-4.53	2.00	3.15
	Pr>|t|	**0.00**	**<.001**	**0.85**	**0.00**	**0.001**	**<.001**	**0.05**	**0.002**
K balance	**PE**	-21.8	-0.28	0.005	0.006	-0.07	0.01	0.001	0.000
R^2 = 0.42, n = 92	**SE**	34.7	0.10	0.001	0.001	0.12	0.06	0.000	0.000
	tValue	-0.63	-2.86	4.59	5.84	-0.60	0.25	2.53	0.20
	Pr>|t|	0.53	**0.005**	**<.0001**	**<.0001**	0.55	0.80	**0.01**	0.84
C balance_Janssen	**PE**	-894	1.84	0.18	0.04	0.57	0.92	-0.01	0.000
R^2 = 0.87, n = 128	**SE**	154	0.67	0.01	0.01	0.39	0.29	0.003	0.000
	tValue	-5.81	2.73	24.96	6.03	1.49	3.18	-2.3	-0.67
	Pr>|t|	**<.001**	**0.007**	**<.001**	**<.001**	0.14	**0.002**	**0.023**	0.50
C balance_Yang	**PE**	-936	2.05	0.15	0.09	0.72	1.04	-0.01	0.000
R^2 = 0.85, n = 128	**SE**	168	0.73	0.01	0.01	0.42	0.32	0.003	0.000
	tValue	-5.58	2.79	19.17	11.98	1.71	3.3	-2.34	-0.88
	Pr>|t|	**<.001**	**0.006**	**<.001**	**<.001**	**0.09**	**0.001**	**0.021**	0.38
C balance_Cai	**PE**	-1175	2.14	0.09	0.11	0.47	1.02	-0.01	0.000
R^2 = 0.76, n = 128	**SE**	187	0.82	0.01	0.01	0.47	0.35	0.004	0.000
	tValue	-6.3	2.62	10.49	12.56	1	2.91	-2.23	-0.22
	Pr>|t|	**<.001**	**0.01**	**<.001**	**<.001**	0.32	**0.004**	**0.028**	0.82
SEN_0-20cm	**PE**	166	0.05	0.001	0.002	-0.26	-0.11	-0.000	0.000
R^2 = 0.37, n = 128	**SE**	14.3	0.06	0.001	0.001	0.04	0.03	0.000	0.000
	tValue	11.6	0.76	1.50	2.56	-7.17	-4.05	-0.11	6.32
	Pr>|t|	**<.0001**	0.45	0.14	**0.01**	**<.001**	**<.001**	0.91	**<.001**
SEN_20-40cm	**PE**	146	0.09	0.000	0.001	-0.22	-0.12	0.000	0.000
R^2 = 0.50, n = 127	**SE**	12.5	0.05	0.001	0.001	0.03	0.02	0.000	0.000
	tValue	11.74	1.66	0.22	1.60	-6.95	-5.19	0.33	5.65
	Pr>|t|	**<.001**	0.10	0.82	0.11	**<.001**	**<.001**	0.74	**<.001**
SEP_0-20cm	**PE**	38.7	0.17	0.000	0.001	0.01	-0.08	-0.000	-0.000
R^2 = 0.47, n = 128	**SE**	10.4	0.05	0.001	0.001	0.03	0.02	0.000	0.000
	tValue	3.73	3.84	0.48	1.91	0.39	-4	-1.27	-1.09
	Pr>|t|	**0.001**	**0.001**	0.63	**0.059**	0.70	**0.001**	0.21	0.28
SEK_0-20cm	**PE**	101	0.06	0.002	0.002	-0.008	-0.02	-0.000	0.000
R^2 = 0.09, n = 93	**SE**	24.2	0.07	0.001	0.001	0.09	0.04	0.000	0.000
	tValue	4.16	0.91	2.27	2.38	-0.10	-0.48	-1.01	0.05
	Pr>|t|	**<.001**	0.37	**0.03**	**0.02**	0.92	0.64	0.32	0.96

PE = Parameter Estimate; SE=Standard Error

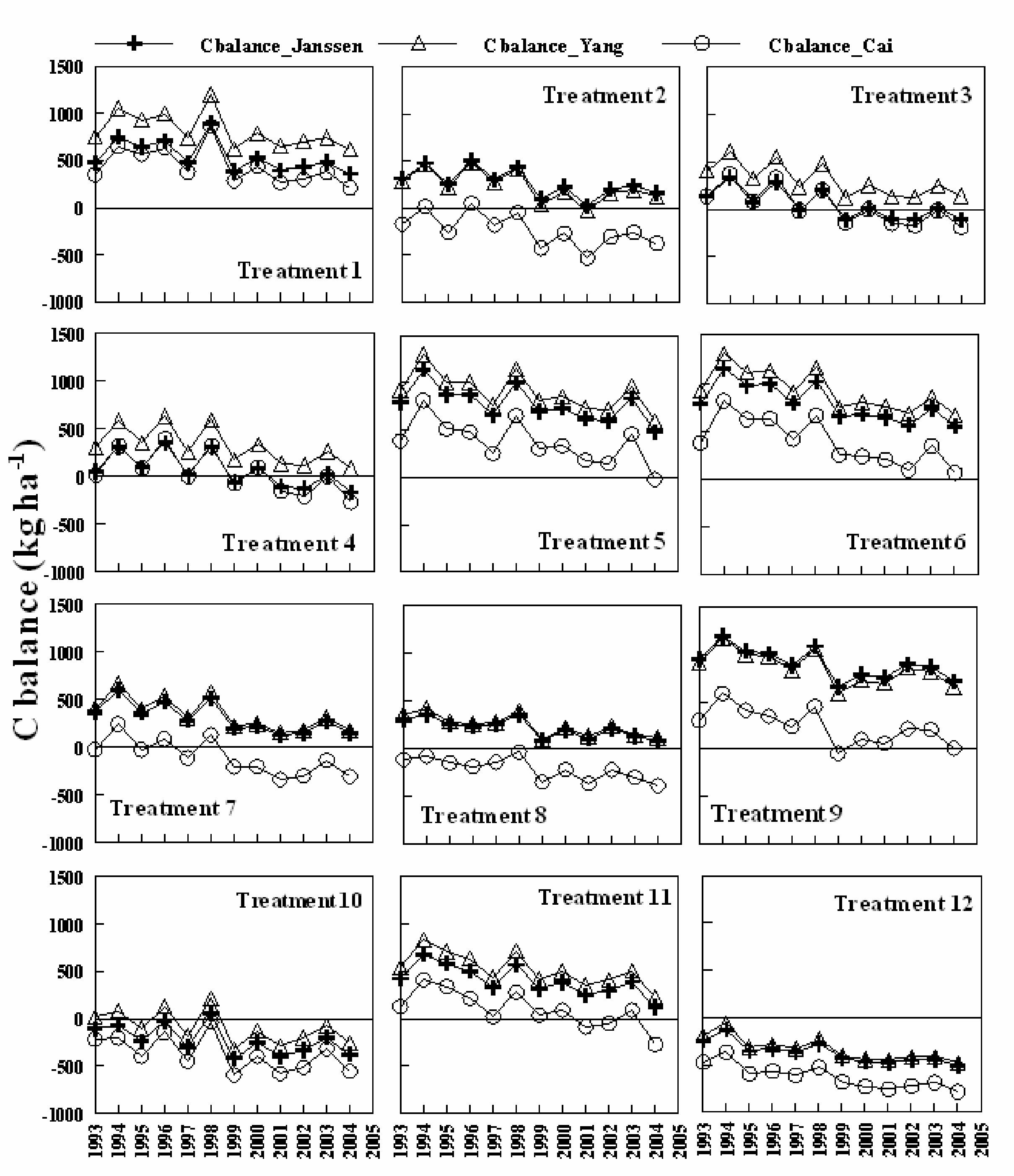


Fig. 6.2 Calculated C balances per treatment during the experimental period 1993 - 2004. Balances were calculated using different decay coefficients, following Janssen (1992), Yang (1996) and Cai (1996). See also text. Lines between dots are shown for reasons of clarity; they do not have other meanings.

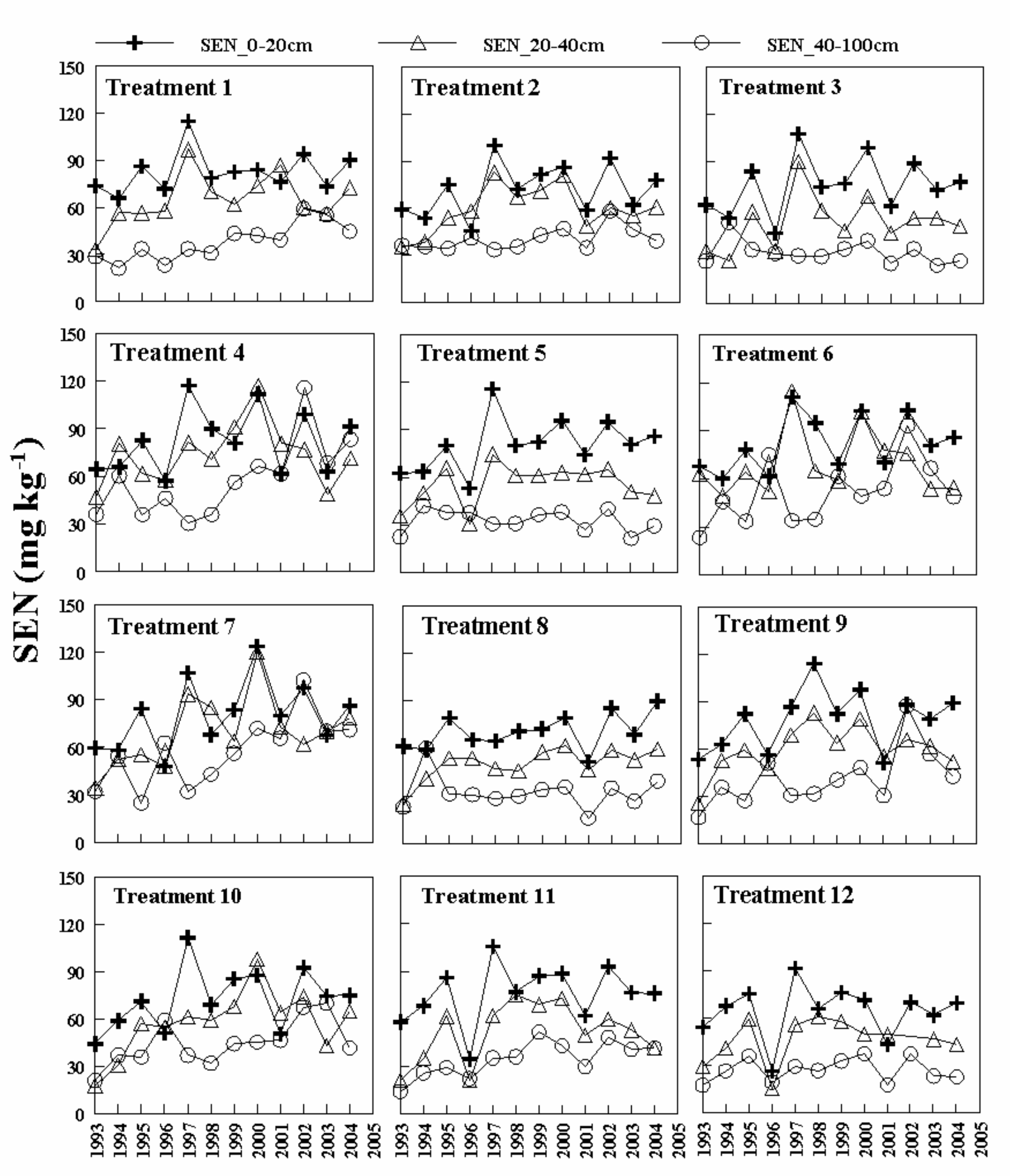


Fig. 6.3 Extractable soil N (SEN) at the end of the growing season per treatment for soil depth 0-20, 20-40 and 40-60 cm. Lines between dots are shown for reasons of clarity; they do not have other meanings.

In the topsoil, SEN was slightly higher in manured and fertilized treatments than in the control treatment, but differences were relatively small and greatly varied from year to year (Figure 6.3). In contrast, subsoil layers exhibited increasing differences between the control treatment and treatments receiving N fertilizer at rates ≥ 105 kg ha^{-1} yr^{-1}. The accumulation of SEN in subsoil layers suggests downward movement of N through leaching. Accumulation of SEN in the subsoil was most pronounced in treatment 7, which received the highest N fertilizer doses, and in the second half of the experimental period, when aboveground biomass and N uptake were relatively low.

Annual variations in SEN were strongly related to SWS and GSR; the higher SWS and GSR, the lower SEN in the 0-20 and 20-40 cm layers (Table 6.3). These inverse relationships are caused by the positive relationship between SWS and N uptake, and GSR and N uptake. However, the significant linear and quadratic relationship between GSR and SEN may also point at N losses via leaching and possibly denitrification in wet years. Interestingly, SEN in the 0-20 cm layers was related to added manure but not to added N fertilizer (Table 6.3).

Soil organic carbon (SOC) in the top 20 cm and in the layer 20-40 cm did not change much over time, and differences between treatments at the end of the experimental period were relatively small (Figure 6.4). In treatments receiving relatively large amounts of stover, manure and N fertilizer, topsoil SOC tended to increase with time. At the end of the experimental period, average SOC in the topsoil was 15.7±0.9 g kg^{-1}, which is 0.8 g kg^{-1} higher than at the start of the experiment. In the 20-40 cm layer, mean SOC content was 11.2 g kg^{-1}. Differences between topsoil and subsoil did not increase over time.

6.3.4 Extractable soil P and K per treatment and year

Extractable P (SEP) in the top soil was strongly related to added NP fertilizer, and also to added manure (Table 6.3). In all treatments SEP tended to increase with time, except for the control treatment (Figure 6.5), which had a strong negative P balance. Treatment 8 also exhibited an increase in SEP in the topsoil from 7 to about 20 mg kg^{-1}, even though the P balance was highly negative (Table 6.1, Figure 6.1). This suggests a priming effect; the added stover and manure in treatment 8 have contributed to increasing the extractability of soil P (Olsen P). This effect was most noticeable during the first half of the experimental period. In the control treatment, SEP ranged between 5 and 9 mg kg^{-1} (mean 7 mg kg^{-1}), and tended to decrease over time.

With time, SEP tended to increase also in the subsoil at depth of 20-40 cm, except for the control treatment. The pattern of increase was irregular and suggests that spatial variations in ploughing depth and slight variations in sampling depth, in addition to leaching, may have contributed to the apparent increasing SEP values at depth of 20-40 cm. Increases in SEP were largest in treatments receiving P fertilizer at rates ≥ 105 kg P_2O_5 ha^{-1} yr^{-1}. No increases were observed at depth of 40-60 cm (not shown).

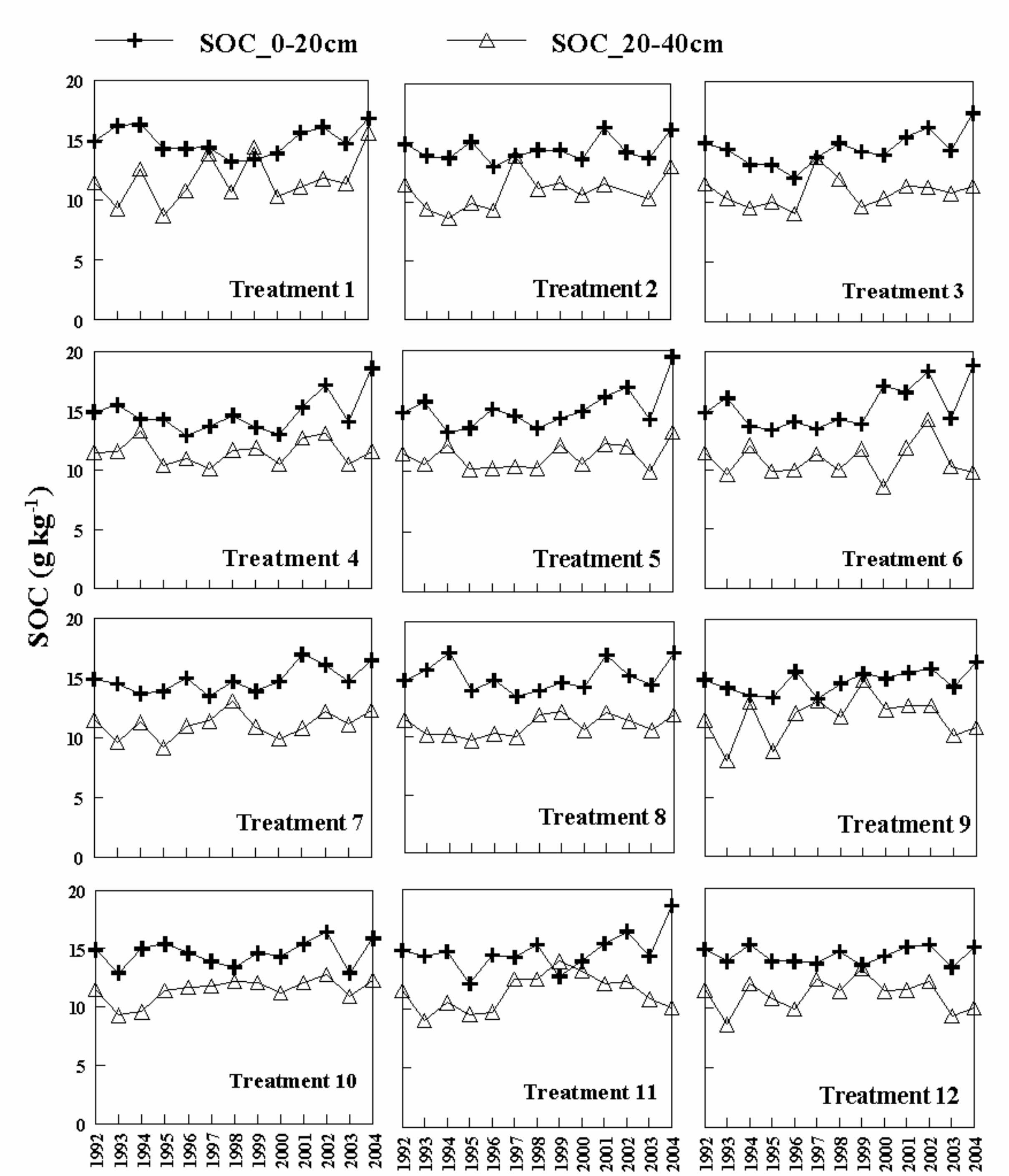


Fig. 6.4 Soil organic carbon (SOC) at the end of the growing season per treatment for soil depth 0-20 and 20-40 cm. Lines between dots are shown for reasons of clarity; they do not have other meanings.

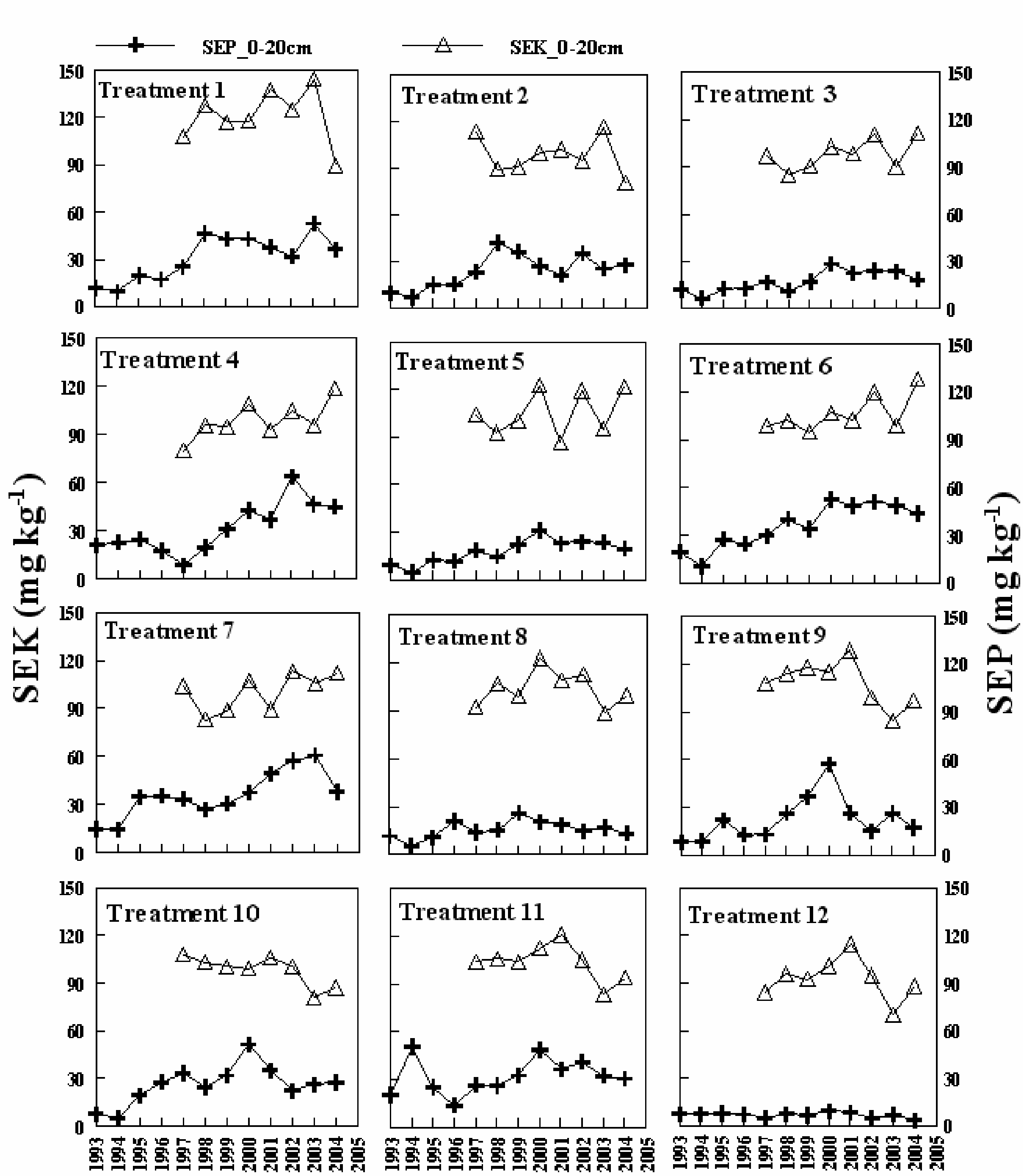


Fig. 6.5 Extractable soil P (SEP) and extractable soil K (SEK) at the end of the growing season per treatment in the top soil (0-20cm). Lines between dots are shown for reasons of clarity; they do not have other meanings. Note that SEK analyses started in 1997.

Soil extractable K (SEK) ranged between 60 and 150 mg kg^{-1}, equivalent to 1.5 to 3.8 mmol kg^{-1}. Over time, SEK remained rather stable or tended to decrease slightly (Figure 6.5), which contrasts with the highly negative K balances in all treatments but 2 (Table 6.1, Figure 6.1). SEK was positively related to added stover and manure. Subsoil (20-40 cm) SEK was on average 75 mg kg^{-1} and remained constant during the period that K was analyzed (1997-2004).

6.4 Discussion and conclusions

6.4.1 Long-term field experiments and deriving fertilization recommendations

This study was originally set-up to deriving N fertilizer recommendations for maize under reduced tillage conditions, as function of added stover and animal manure. Reduced tillage with direct seeding of maize in the soil without prior tillage in spring was introduced in the 1980s and 1990s because it is highly effective in minimizing wind erosion in spring (Cai et al., 2002; Wang et al., 2006). However, this practice necessitates to applying any stover, manure and fertilizers after harvest in autumn, because application in spring without tillage would lead to high risks of being blown away by the incidental strong winds. Applying organic residues and fertilizers 6 to 7 months before seeding is only applicable when possible nutrient losses via run off, leaching and denitrification are negligible. Evidently, this reduced tillage practice creates a possible trade-off between decreased wind erosion and increased nutrient losses before the growing season. Nutrient losses during the winter season were assumed to be very small because of the cold and dry weather (Chapter 3). Results so far suggest indeed that N losses during the winter season are small (Wang et al., 1997; Wang et al., 2003c), and that the N recoveries from applied N fertilizer, stover and manure are relatively high, when applied in optimum ratio (Chapter 5).

Recommendation for N fertilizer should account for any other sources of N, including crop residues and animal manure. For the highest possible N use efficiency, other nutrients should not be limiting. Fertilizer P was applied proportional to N fertilizer, but K (and other nutrients) was not considered, initially. In the attempt to increasing grain yield in Southeast Asia, the prime focus has been on adding N fertilizer, and secondly on adding P fertilizer, while K has received much less attention (Jin et al., 1999; Dobermann et al., 1996, 1998; Ladha, et al., 2003; Fan et al., 2005; Hoa et al., 2006). This neglect of K has led to negative K balances (Figure 6.1) and to declining yields over time (Chapter 5). Only two treatments (5 and 6) did have slightly positive K balances, due to the relatively large inputs of K via both stover (37 kg ha^{-1} yr^{-1}) and manure (33 kg ha^{-1} yr^{-1}). Adding stover and manure has been highly instrumental for supplying K, but also for supplying N and effective organic C to the soil (Figure 6.2). Such multiple effects of animal manure and organic residues have greatly contributed to the world wide increased and renewed interests in organic residues and manure (e.g., Schröder, 2005; Zingore et al., 2006).

Annual variations in NPK and C balances and in extractable soil N, P and K after harvest were large. These variations were mainly related to the large annual variations in the amounts of soil water at seeding (SWS) and growing season rainfall

(GSR), though small-scale soil variations may also have contributed to variations in SEN, SEP and SEK. The large fluctuations between years indicate that long-term measurements are needed for establishing reliable mean nutrient balances in rainfed cropping systems. The trend of decreasing balances (for treatments with negative balances) or increasing balances (for treatments with positive balances) with time was in part also related to decreasing SWS and GSR over time, as these contributed to a decrease in N, P and K uptakes (Chapter 5). This again emphasizes the need for long-term records, to be able to separate the effects of changes in GSR from increasing or decreasing nutrient deficiency due to changes in soil fertility level (Fan et al., 2005).

6.4.2 Soil organic matter

Soil organic matter is crucial to the sustainability of crop production, but there is an ongoing debate about the pros and cons of C sequestration in soils and about the minimum and optimum levels of SOC contents (Feller and Beard, 1997; Loveland and Web, 2003; Janssen and Willigen, 2006b; Janzen, 2006). Reduced tillage and adding crop residues and animal manure aims at maintaining or increasing SOC (e.g., Franzluebbers, 2002) and our results indicate indeed that SOC contents were slightly increasing during the experimental period in the top soil of various treatments (Figure 6.4). However, the relationship between cumulative C balance and SOC content in the top soil was weak (R^2 = 0.4 – 0.6) and depended on the chosen decay coefficients used in the calculation of the C balances (Figure 6.6). Linear regression coefficients ranged from 11 – 17 * 10^{-5}, indicating that 6000 – 9000 kg ha^{-1} of effective organic C was needed to increase the SOC content in the 0-20 cm layer by 1 g kg^{-1}. These amounts are 2-4 times larger than the amount of C in the top soil represented by 1 g kg^{-1}, suggesting that our simple calculations greatly underestimated the decay of SOC. The results presented in Figure 6.6 also allow the interpretation that a negative C balance leads to a decrease in SOC, (in treatments with little or no inputs of organic residues and NP fertilizer), while a positive C balance does not lead to a significant increase in SOC. A SOC content of around 15 g kg^{-1} in the topsoil is above critical levels set for deterioration of soil physical properties and impairment of nutrient cycling mechanisms (Loveland and Webb, 2003; Janssen and de Willigen, 2006a, 2006b; Janzen, 2006). We conclude that there is no pressing need to further increase SOC content at the study site, judged from soil physical and agronomic points of view. A mean SOC content of 15 g kg^{-1} is also above the level of 'ideal soil fertility', for obtaining a target yield of 10 Mg ha^{-1} at 'equilibrium' fertilization, where required N input is equal to N withdrawal with harvested crop (Janssen and de Willigen, 2006a).

6.4.3 Soil fertility indices and nutrient balances

Classical soil fertility rating is based on relationships between soil test values and the crop response to added nutrients. The set-up of such rating systems requires extensive and long-term field testing, while the application in practice presumes that

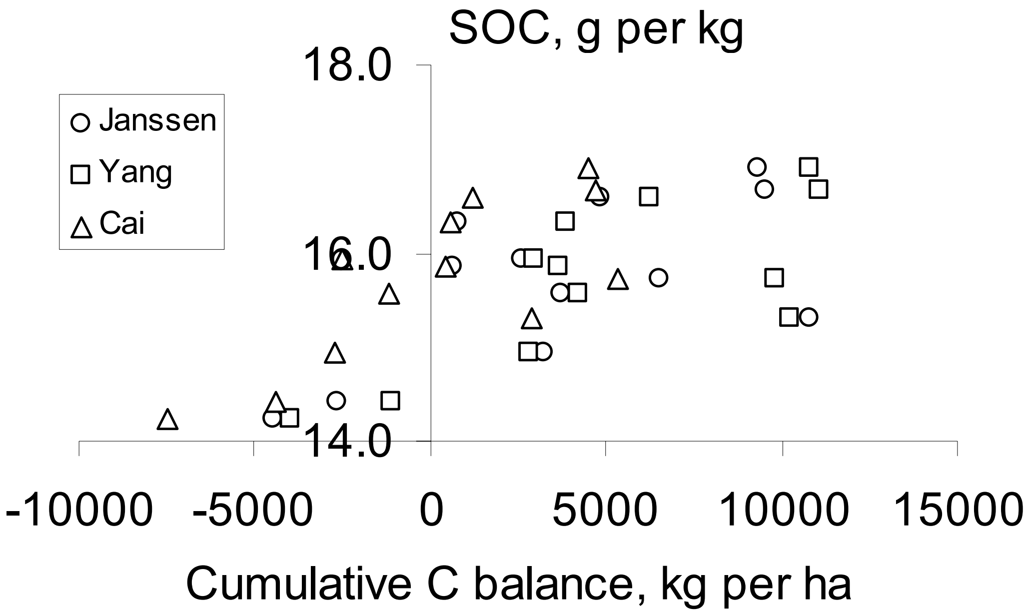


Fig. 6.6 Relationship between the calculated cumulative C balance and the SOC of the top soil (0-20 cm) at the end of the experimental period per treatment. Cumulative C balances were calculated assuming simple first order kinetics, using decay coefficients given by Janssen, (1992), Yang (1996) and Cai (1996). See text.

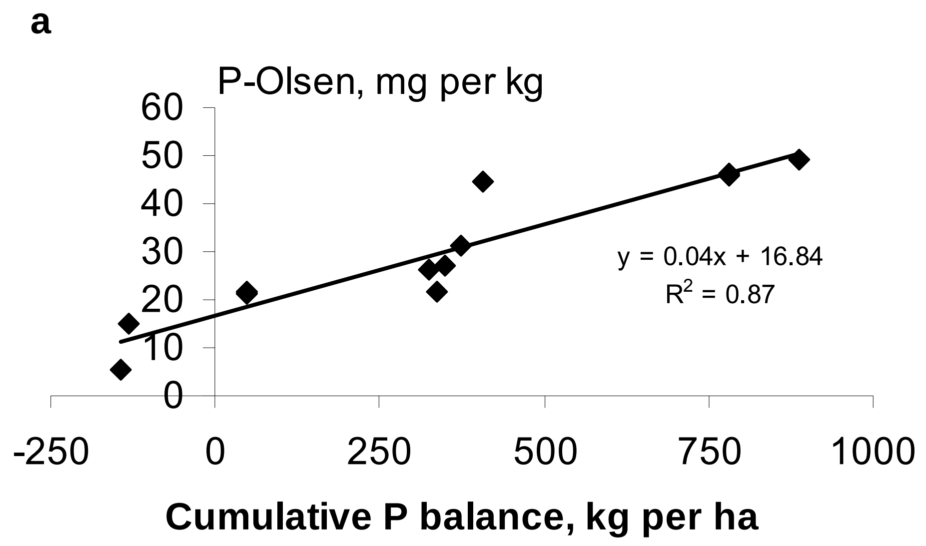
farmers do regular soil testing (Tisdale et al., 1985). Both requirements are not met in northern China, and there is an ongoing search for simple, effective and efficient recommendation systems that also account for possible environmental side-effects (Zhang et al., 2005). Nutrient balances provide easy to obtain proxies for the potential environmental effects, but the actual impact of a balance cannot be understood properly without considering the actual soil fertility (Oborn et al., 2003; Janssen and de Willigen, 2006a; 2006b). This holds especially when residual effects are to be expected as is the case with added manure and crop residues and P fertilizers in general.

Mean negative balances of N, P and K were observed in treatments 8 and 12, negative N and K balances combined with positive P balances in treatments 2, 3, 9 and 10, and negative N but positive P and K balances in treatment 5. Mean positive N and P balances combined with negative K balances were observed in treatments 1, 4, 7 and 11, while positive balances of N, P and K were found in treatment 6 only. This multitude of combinations reflects the complexity of balanced fertilization (Janssen, 1998). Negative N, P, K and C balances in various treatments coincided in most cases with decreases in extractable soil N, P and K, and SOC contents indicating that the partial balances are a good proxy for evaluating soil resource depletion.

The relationship between cumulative P balances over the experimental period and mean SEP (P-Olsen) at the end of the experimental period is shown in Figure 6.7a. Cumulative P balances ranged from -144 to 888 kg P ha^{-1}, and SEP from 5 to 49 mg kg^{-1}. The regression coefficient of the linear relationships suggests that only a fraction (roughly 10%) ends up as extractable P. Blake et al (2003) found a higher recovery (10-40%) with 0.5 M $NaHCO_3$ (extracting agent used in P-Olsen method) in soils from long-term field experiments in Rothamsted, United Kingdom, even though they applied an initial extraction using resin strips. Richards et al. 1999 found that 13% of the increase in total soil P, following long-term P fertilization, remained soluble by the Olsen method. Differences between soils in the fraction of total soil P extractable by P-Olsen may be related to differences in sorption characteristics, P saturation index and soil pH. The relatively low P-Olsen extractability in the current experiment suggests that the P saturation index is low, but there are no experimental data available to substantiate this. Interestingly, treatments with manure and stover as main P source gave a stronger response in P-Olsen than treatments with P fertilizer as main P source. This is most clear for the treatments with a cumulative P surplus in the narrow range of 324-408 kg ha^{-1} with SEP ranging from 22-45 mg P kg^{-1}; here SEP was linearly related to the amount of P applied with manure. The positive effect of manure and stover on SEP also follows from the two treatments with a negative P surplus (Figure 6.7). Such positive effects of manure and crop residues on the extractability of soil P have been reported before for long-term manuring experiments (Olsen and Barber, 1977) and tillage experiments (Hussain et al., 1999; Delgado et al., 2002).

The relationship between cumulative K balances over the experimental period and mean SEK (Exchangeable K) at the end of the experimental period are shown in Figure 6.7b. Cumulative K balances ranged from -516 to 144 kg ha^{-1}, and SEK ranged from 2.0 to 3.0 mmol kg^{-1}. There was a weak linear relationship between cumulative K surplus and SEK; the small regression coefficient suggests that the exchangeable K pool in the soil is strongly buffered by recalcitrant K pools in the soils (c.f. Hoa et al., 2006). Mining of the soil for 12 consecutive years did not lead to a decrease in SEK. Conversely, SEK averaged over all treatments was slightly higher at the end than at the start of the experiment. Again, SEK values were higher in treatments with relatively large doses of manure and stover compared to treatments with small doses of organic residues, suggesting that organic residues facilitated the transfer of K from recalcitrant K pools to the exchangeable K pool.

Janssen and de Willigen (2006b) classified ratios of soil test values of N, P and K in terms of relative input requirements of N, P and K. Ratios of SOC $(\text{P-Olsen})^{-1}$ <0.16 were classified as extremely N deficient requiring only N input and ratios of >1.37 were classified as P deficient, requiring inputs of N and P in the ratio < 3.5. At the start of the experiment, the ratio SOC $(\text{P-Olsen})^{-1}$ was 2.1, suggesting that the ratio for N and P inputs should be < 3.5. The N:P ratios in fertilizer, manure and stover were 2.3, 5.5 and 17, indicating that NP fertilizer gave the best match.



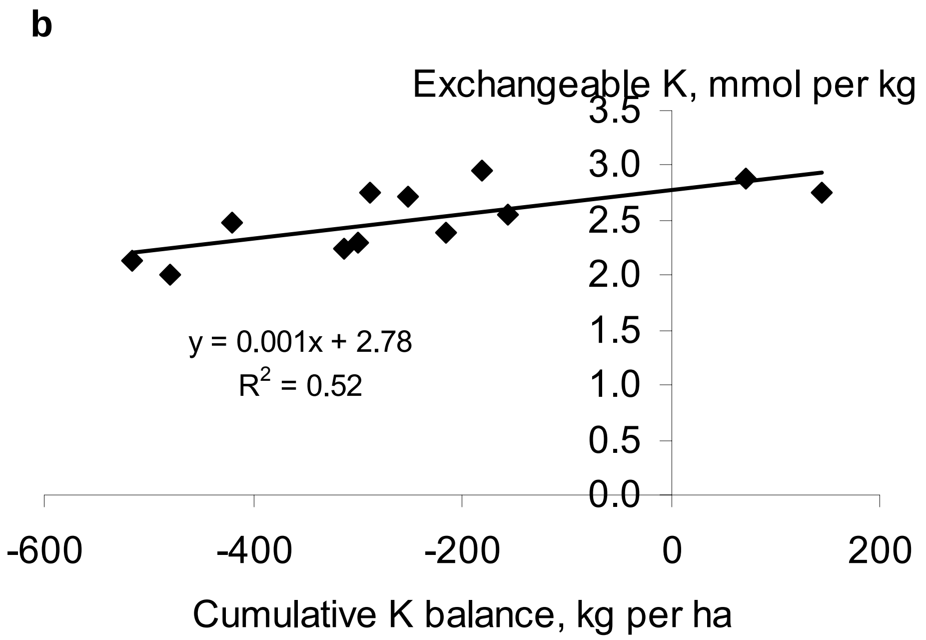


Fig. 6.7 Relationship between the cumulative P balance and extractable soil P (P-Olsen) in the top soil (upper panel), and between the cumulative K balance and extractable soil K (Exchangeable K) in the top soil (lower panel), at the end of the experimental period per treatment.

Janssen and de Willigen (2006b) classified ratios of SOC (Exchangeable K)$^{-0.5}$ < 4.6 as extremely N deficient and ratios of >12.9 as extreme K deficient requiring only K input. At the start of the experiment, the ratio SOC (SEK)$^{-0.5}$ was 10.3, suggesting that the ratio of N and K inputs should be <1. The N:K ratios in manure and stover were 0.9 and 1.3, respectively, indicating that stover gave the best match. At the end of the experimental period ratios of SOC $(SEP)^{-1}$ ranged from 0.3 – 1.0 for the fertilized and manured treatments to 2.7 for the control treatment (Table 6.4). Ratios of 0.3 – 1.0 have been classified as moderate N deficiency, requiring N:P input ratios of 3.5-7, while a ratio of 2.7 has been classified as P deficient, requiring N:P input ratios of <3.5 (Janssen and De Willigen, 2006b). Ratios of SOC $(SEK)^{-0.5}$ were still high (range 9-10) in all treatments at the end of the experimental period, suggesting K deficiency. This classification is in line with the negative K balances observed in most treatments (Figure 6.1).

6.4.4 Soil fertility and nutrient management in dryland farming

Soil fertility and nutrient management research is concerned ultimately with providing management information and viable options to farmers to make better decisions. The quality of this information is intimately tied to its value; it fails if it does not lead to economic and social (and environmental) benefits. Commonly, smallholder farmers in dryland areas do not invest in soil fertility, mainly because of the economic risk of such investments in drought-prone climates. There is often also a lack of information about the profitability of soil fertility investments and fertilizer use under diverse and risky environmental conditions, while such conditions require highly skilled management. This is also pertinent to northern China, even though fertilizers are heavily subsidized. In the attempts to increase crop production and to overcome the information gap, simple blanket fertilizer recommendations are promoted, where site-specific and weather-dependent management measures are needed. Tailoring of crop management practices to the expectations of the season in progress is what farmers in this region are doing, but this holds less for soil fertility and nutrient management.

Target soil fertility and target nutrient inputs should reflect target crop yields (Janssen and de Willigen, 2006b), but how to answer this question for rainfed areas where 'target' maize yields may range from more than 10,000 in relatively wet years to less than 3000 kg ha^{-1} in relatively dry years? Soil fertility and nutrient management should respond to such variable conditions, in a way commonly termed as 'response farming' (Stewart, 1991). From economic and environmental points of view, it would be rather unwise to strive at high soil fertility levels under such conditions. Instead, soil fertility should be tailored to a level where losses of soil nutrients are minimal, while target yields for the relatively wet years can still be realized with proper doses of input nutrients. The 'ideal soil fertility level' for mean target yields of 7000 kg ha^{-1} may be a proper target level, with P-Olsen values around 20 mg kg^{-1} and exchangeable K around 2 mmol kg^{-1}, and assuming a SOC content of 15 mg kg^{-1}. The quantity of input nutrients should be tailored to target yields of cf. 10 Mg ha^{-1}, but the N should be split applied, with a major portion before seeding and a supplemental portion dependent on rainfall expectation at the 4-6 leaf stage (Schröder et al., 2000).

Table 6.4 Mean soil fertility indices per treatment at the end of the experimental period. Treatments are arranged in order of increasing grain yield (see table 1). Ratios of soil organic carbon (SOC) versus extractable soil phosphorus (SEP), and SOC versus extractable soil potassium (SEK) are explained in the text.

Treatment	Treatment inputs, kg ha^{-1}			SOC	SEP	SEK	SOC	SOC / SEP	SOC/(SEK)$^{0.5}$
	Fertilizer	Stover	Manure	g kg^{-1}	mg kg^{-1}	mmol kg^{-1}	g kg^{-1}		
12	0	0	0	14.2	5.3	2.0	14.2	2.7	10.1
8	0	3000	1500	15.9	15.2	2.4	15.9	1.0	10.3
3	31	879	4500	15.9	21.1	2.6	15.9	0.8	9.9
10	105	0	1500	14.4	27.0	2.1	14.4	0.5	9.9
4	179	879	4500	16.3	46.0	2.7	16.3	0.4	9.9
5	31	5121	4500	16.9	21.6	2.7	16.9	0.8	10.2
7	210	3000	1500	15.6	49.4	2.8	15.6	0.3	9.4
2	105	3000	0	14.9	26.3	2.5	14.9	0.6	9.5
6	179	5121	4500	16.7	46.4	2.9	16.7	0.4	9.8
11	105	3000	3000	16.6	31.4	2.2	16.6	0.5	11.1
1	105	3000	6000	15.7	44.5	3.0	15.7	0.4	9.1
9	105	6000	1500	15.3	21.7	2.3	15.3	0.7	10.1

As an example and for average rainfall conditions, Figure 6.8 presents N and K balances as function of added N fertilizer, cattle manure and stover. Clearly, N balances are strongly related to N fertilizer input, while K balances are also related to stover and manure inputs. Neutral balances (input = output) relate to 'ideal soil fertility', i.e., the soil nutrients and input nutrients together satisfy the nutrient demand by the crop. Without manure, N fertilizer inputs should be in the range of 140-100 kg ha^{-1} for stover inputs in the range of 0-8000 kg ha^{-1}. With 6000 kg ha^{-1} of cattle manure as basal dressing, N fertilizer inputs should be in the range of 80-20 kg ha^{-1} for stover inputs in the range of 0-8000 kg ha^{-1}.

6.4.5 Conclusions

Reduced tillage combined with modest inputs of organic residues maintained soil organic carbon (SOC) content at the initial levels of 15 g kg^{-1} in the topsoil (0-20 cm) and at 11 g kg^{-1} in the subsoil (20-40 cm). Increased inputs of effective C only marginally increased SOC contents in the topsoil. The available evidence indicates that there is no real prospect and need for increasing SOC contents beyond current levels.

Partial N, P and K balances were strongly related to added NP fertilizer, stover and animal manure, and to growing season rainfall. Most treatments had a positive P balance, which led to increases in extractable soil P (P-Olsen). However, only a fraction of the P added to the soil was extractable. Most treatments had negative K balances, but these negative K balances did to lead to a strong drop in exchangeable soil K. The rather weak relationship between K balances and exchangeable K indicates that the soil has a high K buffering capacity.

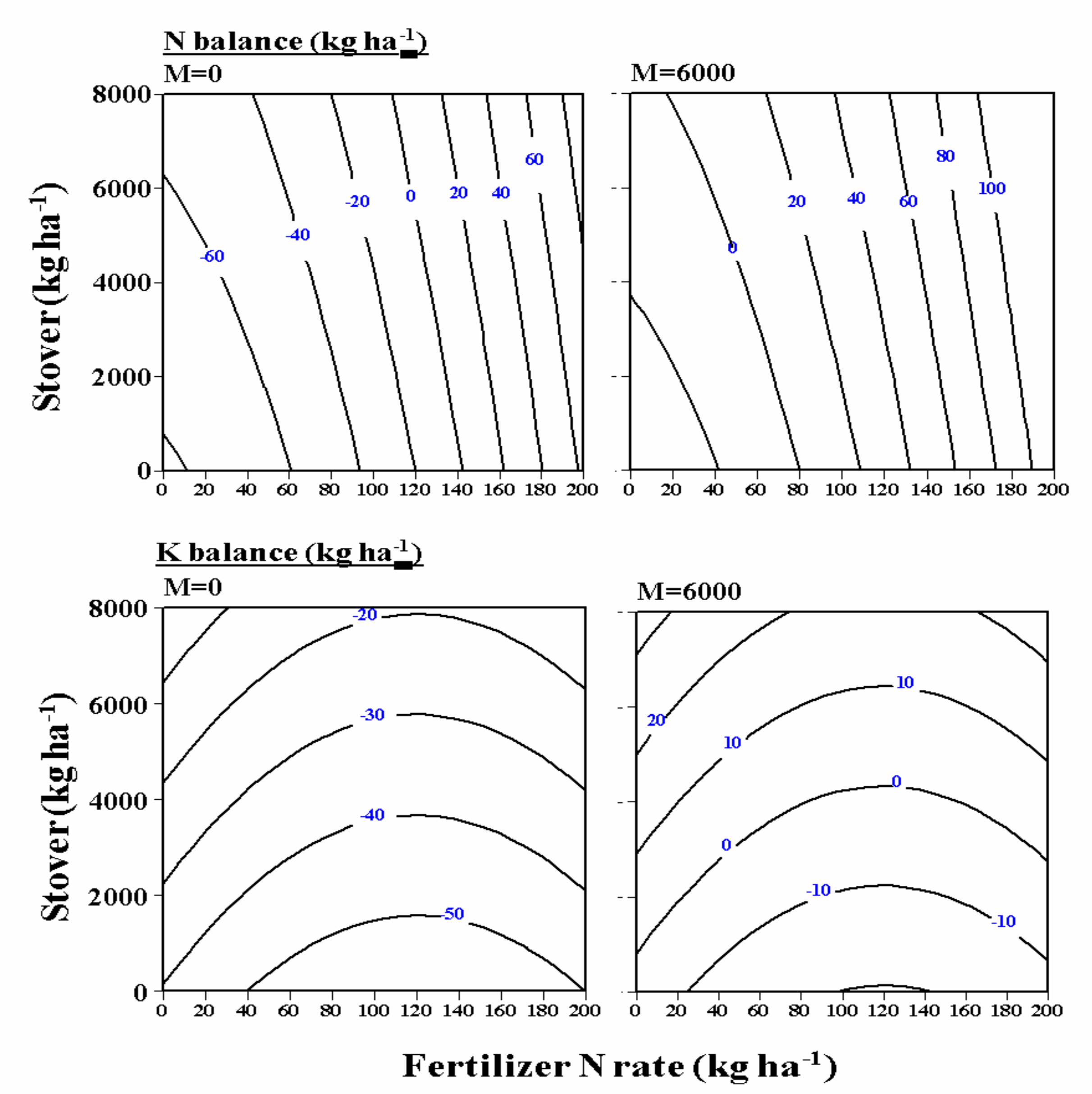


Fig. 6.8 Calculated relationships between added stover, manure and N, and partial N balnces (upper panels) and K balances (bottom panels) for mean GSR and SWS, using the equations presented in Table 2.

The analysis of nutrient balances and soil fertility indices revealed that nutrient inputs in most treatments were far from balanced. Balanced fertilization under conditions of variable rainfall is indeed highly complicated. The concept of 'ideal soil fertility level' is applicable in principle to variable rainfall conditions, but the definition of target yield and the partitioning of basal and supplemental N dressings need further examination. It is concluded that nutrient management should become an integral part of the 'response farming' in this drought-prone area.

7 Scenario analysis of tillage, residue and fertilization management effects on soil organic carbon dynamics

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Summary

Based on 10-year field data from experiments on residue/fertilizer management in the dryland farming region of northern China Century model was used to simulate the site-specific ecosystem dynamics through adjustment of the model's parameters, and the applicability of the model to propose soil organic carbon (SOC) management, temporally and spatially, in cases such as of tillage/residue/fertilization management options, was identified via scenario analysis. Results between simulations and actual measurements were in close agreement when appropriate applications of stover, manure and inorganic fertilizer were combined. Simulations of extreme C/N ratios with added organic materials tended to underestimate the measured effects. Scenarios of changed tillage methods, residue practices and fertilization options showed potential to maintain and enhance SOC in the long run, while increasing inorganic N slowed down the SOC turnover rate but did not create a net C sink without any organic C input. The Century model simulation showed a good relationship between annual C inputs to the soil and the rate of C sequestration in the top 20 cm layer and provided quantitative estimations of changes in parameters crucial for sustainable land use and management. Conservation tillage practices for sustainable land use should be integrated with residue management and appreciable organic and inorganic fertilizer application, adapted according to the local residue resource, soil fertility and production conditions. At least 50% residue return into the soil was needed annually for maintenance of SOC balance, and manure amendment was important for enhancement of SOC in small crop-livestock systems in which crop residue land application was limited.

Keywords: *Century model, conservation tillage, crop residue, dryland, soil organic carbon*

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7.1 Introduction

The region of dryland farming in northern China accounts for about 55% of the nation's total cultivated land area (Xin and Wang, 1999). Much of the land in the region is hilly and rainfed, subjected to severe water and soil erosion, as well as soil denudation. Conventional farming systems in these areas characteristically used a moldboard plow at a depth of 16--18 cm, intensive plowing with several operations for one crop cultivation, and clean plowing with all crop straw or residue removed from the topsoil usually by burning or being taken as fodder for animals in some areas. Fertilization management is often poor, with low fertilizer use rates and unbalanced N:P:K nutrient ratios in much of the hilly land due to inadequate capital and technology as well as low organic fertilizer input due to the slow development of the animal industry (Wang et al., 1999). Both natural factors and human activities contribute to several negative effects on 1) the environment, including topsoil loss, water runoff, and nutrient loss; 2) land productivity, including fertility degradation, soil structure deterioration and decline in soil water retention with soil organic matter (SOM) depletion; and 3) depressed financial situation, such as reduced resource-use efficiencies of fertilizer, water, energy, and labor.

Because of its function in protecting soil structure stability from erosion, increasing water capacity for plant growth, improving soil fertility for land sustainability, and contributing to soil C sink for mitigating CO_2 emission (Ellert and Janzen, 1999) soil organic matter was one of the most important soil components, a multi-element nutrient resource, the most important indicator of soil quality and a critical factor for sustaining soil quality (Reeves, 1997). Tillage is a major cause of organic matter depletion when native ecosystems are converted to agriculture (Six et al., 2000), and has caused a 50%-70% reduction in the initial SOC level (Lal and Bruce, 1999). Soil disturbance increases the rate of macroaggregate turnover and reduces the formation of stable microaggregates in which carbon is stabilized (Six et al., 2000).

Thus, conservation management practices as a means of increasing the potential sink for carbon of cultivated soils have received much interest. Long-term studies have shown the benefit of improved management practices such as adequate fertilization, manures, conservation tillage and residue return on maintaining agronomic productivity in increasing C inputs into the soil (Reeves, 1997), reducing environmental impact by mitigating CO2 emission, and increasing economic returns through reduced labor requirements, time savings, reduced machinery and fuel savings. For China, Lal (2002) suggested that the low SOC concentration in soils could be enhanced by 1) restoration of degraded soils, 2) conversion of agriculturally marginal soils to pastures or forest lands, and 3) adoption of recommended management practices on cropland. Recommended practices included returning crop residues to the soil, adopting conservation-effective farming systems and nutrient recycling management technologies that reduced risks of soil erosion and improved soil fertility.

Preliminary studies from 1980 to 2002 (Gao et al., 1990, 1991; Wang et al., 1995, 2003a, 2003b; Cai et al., 1994, 1995, 1998; Cai and Wang, 2001; Cornelis et al., 2002; Wang and Cai, 2000, 2001, 2003; Wang et al., 2003a, 2003b) showed that conservation tillage practices improved water storage, nutrient balance, crop yield, and water and fertilizer use efficiency. However, information is still sparse on SOC dynamics affected by long-term tillage and residue management for dryland farming systems in nonrthern China. Nevertheless, SOM has been difficult to study because of its complex mixture of substances having turnover rates that range from days to millennia (Trumbore, 1997), variability among sites, soil and environmental variables, and sensitivity to agricultural activities, including selection of tillage methods as well as addition of fertilizers and manure (Reeves, 1997; Fernandes et al., 1997; Lal, 2002).

To improve the understanding of soil C cycling processes related to soil conservation practices (tillage/residue/fertilizer/manure) under dryland soil-crop management systems and in order to develop methodologies for quantitative evaluations of sustainable land use, it was necessary to obtain quantitative estimates by applying simulation models (such as the Century model) linked with relevant field datasets. The Century model, an SOC dynamic process simulation and management model, provides a way to model the trend in SOC change and the potential sink of SOC associated with changed management options. The management options that could be controlled by changing the related model's parameters include fire, fertilization, various cultivation practices and harvest methods. The Century model has been widely used and validated for different types of ecosystems, and extensively used to simulate long-term (30--60 year) dynamics of soil organic matter and plant production for maize as well as winter and spring wheat systems. It has been utilized to evaluate the impacts of management practices and environmental changes on natural and managed ecosystems at the site, regional and global levels (Parton and Rasmussen, 1994; Parton, 1996; Parton et al., 1983, 2001; Paustian et al. 1992; Motavalli et al., 1994; Fernandes et al., 1997; Gilmanov et al., 1997; Kelly et al., 1997; Smith et al., 1997; Chuluun and Ojima, 1999; Mikhailova et al., 2000; Desjardins et al., 2001; Pennock and Frick, 2001; van Santen et al., 2002; Ardö and Olsson, 2003; Carvalho Leite et al., 2004; Hill, 2003; Song and Woodcock, 2003). It could also be used as a tool to help evaluate impacts of the environment and management, to quantitatively forecast and estimate the changes in parameters crucial for sustainable land use under site-specific conditions (soil, climate, system), and to accelerate acceptance of conservation practices. However, the model's performance on dryland farming systems of northern China was untested. Therefore, in this research 10-year field data from experiments on residue/fertilizer management in the dryland farming region of northern China was used to test the Century model's capability to represent the site-specific ecosystem dynamics through adjustment of the model's parameters, and to identify, temporally and spatially, in cases such as of tillage/residue/fertilization management options, its applicability to propose SOC management via scenario analysis.

7.2 Materials and methods

7.2.1 Century model description

The Century model is a process model representing long-term nutrient cycling and soil organic matter (SOM) dynamics for different plant-soil systems including grassland, forest, agricultural land and savanna. The model is composed of a soil organic matter/decomposition sub-model, a water budget sub-model, and two plant production sub-models (grassland/crop and forest) with management and events scheduling functions. The model has been used to simulate the response of these ecosystems to changes in environmental driving variables (maximum and minimum air temperature, precipitation and atmospheric CO_2 levels) and changes in management practices (grazing intensity, forest clearing practices, burning frequency, fertilizer rates, crop cultivation practices, residue and manure application, etc.) (Parton, 1996; Parton et al., 2001; Metherell et al., 1993).

The soil organic matter sub-model includes active, slow, and passive SOM pools, above and below ground litter pools (each partitioned into structural and metabolic components), and a surface microbial pool (Parton et al., 2001). The active pool (approximately 2% of the total SOM pool) includes soil microbes and microbial products with short turnover time (1--3 months). The slow SOM pool (45% to 60% of total soil SOM) includes resistant plant material derived from structural plant material and stabilized soil microbial products (turnover time ranging from 10 to 50 years). The passive pool (45% to 50% of total SOM) includes physically and chemically stabilized SOM that is very resistant to decomposition (turnover time from 400 to 4 000 years). Plant litter materials are split into structural and metabolic materials as a function of the lignin to nitrogen ratio (L:N) of the litter. The structural materials include cellulose, hemi-cellulose and lignin fractions of plant materials (resistant to decomposition), while the metabolic materials are readily decomposable.

The model runs with a monthly time step, functions at the scale of a square meter, and simulates the 0--20 cm surface layer. The major input variables for the model include: 1) climate variables i.e., monthly precipitation, and monthly average maximum and minimum air temperature; 2) site variables, i.e., soil texture, lignin, N, S, and P content of plant material, and soil and atmospheric N inputs; and 3) initial conditions, i.e., initial soil carbon, and nitrogen (phosphorus and sulfur optional). The model can be used to simulate the effects of tillage, residue, fertilization via the management and events scheduling functions. Table 7.1 provides a brief description of the Century model.

7.2.2 Field experiment

Simulations with the Century model were carried out for an experimental site established in 1992 at the Shouyang Dryland Experimental Station, Shanxi Province, in the semi-humid region of northern China. A brief description of the research site is given in Table 7.2. Spring maize was the main crop grown under the one-crop-per-year cropping system in Shouyang. The annual regional precipitation showed large variations from year to year and uneven seasonal distributions. For instance, the

Table 7.1 Description of the Century model

Spatial scales	Plot, field, regional, national, global
Time step	Months
Ecosystems	Grassland, agricultural land, forest, savanna
Data required for input	Weather (rainfall, air temperature), soil and plant (soil texture, soil pH, water holding capacity and wilting point, soil C/N, plant C/N)
Management practices	Rotation, tillage, residue, fertilizer, manure, irrigation
Dynamic processes	SOM dynamics, plant growth, N, P or S cycling
Litter and SOM pools	Structural litter pools, metabolic litter pools, microbial biomass (active SOM pools), slow SOM pools, passive SOM pools

Table 7.2 The location and conditions of the research site in Shouyang, Shanxi Province, China

Location	Elevation	Soil type	Annual rainfall			Average annual temperature	Frost free period
			Average	Maximum	Minimum		
	m		mm			°C	days
37.54° N, 113.10° E	1 100	Sandy loam (Leptosols)[a)]	520	806	235	7.4	130

[a)]FAO/UNESCO, 1993.

annual precipitation for the 11-year period (1993-2003) ranged from 251 mm in a dry year (in 1997) to 675 mm in a wet year (in 1995). Additionally, high rainfall intensity and frequent rainstorms occurred during the summer season (June to September) when about 70% of the annual precipitation occurred. Thus, water shortages arose during the period of maize emergence in spring.

Soils at the study site experienced conventional tillage/residue and fertilization operations including extensive cultivation, low fertilizer (or manure) input, and crop residue removal or burning, which accelerated soil erosion and soil organic matter loss, soil quality degradation, and unstable land productivity. The soil organic matter, total N, available N ($NH4^{+}$+$NO3^{-}$), Olsen P, and available K contents of the soil were 11.4-25.7 g kg^{-1}, 0.87--1.10 g kg^{-1}, 55-83 mg kg^{-1}, 4.6-10.6 mg kg^{-1}, and 93-140 mg kg^{-1}, respectively, with soil pH above 8.0. Due to traditional moldboard plowing both in fall and spring over many years (Wang et al., 1995), the soils usually had a shallow top layer and a hard pan (bulk density about 1.4 Mg m^{-3}) between 17-27 cm depths. This caused an increase in surface evaporation after plowing, and a decrease in rainwater infiltration and an increase in surface runoff and nutrient loss in the rainy season.

Field experiments of residue incorporation combined with fall fertilizer application for spring maize (Zea mays L.) were conducted since 1992. Maize varieties were locally recommended, including Yandan No. 12 used from 1993 to 1997, Shandannong No. 1 in 1998, and Jindan No.34 from 1999--to 2002, at a seeding rate of 30 kg ha^{-1}. The inter-row and row spacing was 30 cm× 60 cm. Maize was sown in late April and harvested in late October, followed by a fallow period from October until the next April. The residue incorporated with the fertilizer application was treated after the maize harvest in the fall, and then sowing was carried out with a no-till drill in the spring. Chemical fertilizers used were urea and superphosphate fertilizers; organic fertilizers included maize stover and cattle manure. The organic matter, total N, total P (P_2O_5), and total K contents were 750 g kg^{-1}, 6.3 g kg^{-1}, 0.88 g kg^{-1}, and 7.2 g kg^{-1}, respectively, for maize stover, and 360 g kg^{-1}, 9.6 g kg^{-1}, 3.9 g kg^{-1} and 7.4 g kg^{-1}, respectively, for cattle manure.

The experimental layout was a D-optimal designe (Xu, 1988), which included 3 factors (fertilizer N, maize stover, and cattle manure) and 11 combined application treatments with two replications, plus treatment 12 as a check (CK) (Table 7.3).

7.2.3 Model parameterization for site studies

Model site parameters that defined the site's climate data, soil physical characteristics and initial organic matter input variables were obtained from experimental data when possible, and provided by the default model parameter sets, which were modified if necessary. Climate input variables for average monthly temperature (minimum and maximum) and monthly precipitation were calculated using the climate data (1990--1999) at the site weather stations in Shouyang (37.54° N, 113.10° E, elevation: 1 061.9 m). Weather data was stochastically generated using the Century model routines.

Soil samples of the top 20 cm at the field were collected before the experiment in 1992 and measured for bulk density (BD), soil texture (or particle size distribution), and organic matter content to provide the initial soil data required for the model run (Table 7.4). One hundred cm3 soil cores were collected for the initial BD determinations. The particle size distribution was determined using a sieving machine and the pipette method (Eijkelkamp, the Netherlands), and expressed as the mass percentages of the fractions of the soil separates that included sand, silt and clay in a soil sample. The organic matter was determined by the K_2Cr2O_7 method after the soil samples were air-dried and ground to pass through a 0.25 mm sieve. The total SOC mass was partitioned as follows: 3% active, 44% slow, and 53% passive (Table IV). Soil samples (0--20 cm layer) were also collected at harvest during 1992--2002 for analysis of organic matter.

Table 7.3 Treatments for field experiments on residue/manure incorporation combined with fall fertilizer application for spring maize (Zea mays L.)

Treatment	Application rate		
	Fertilizer N[a]	Corn stover manure	Cattle manure
	kg ha^{-1}		
1	105.0	3 000	6 000
2	105.0	3 000	0
3	30.8	879	4 500
4	179.3	879	4 500
5	30.8	5 121	4 500
6	179.3	5 121	4 500
7	210.0	3 000	1 500
8	0.0	3 000	1 500
9	105.0	6 000	1 500
10	105.0	0	1 500
11	105.0	3 000	3 000
12	0.0	0	0

[a] Fertilizer N:P_2O_5 = 1:1.

Table 7.4 Century model inputs for simulation of SOC dynamics under dryland farming systems in Shouyang, China

Soil texture			Soil bulk density	Initial SOC			Initial C/N		
Sand	Silt	Clay		Active	Slow	Passive	Active	Slow	Passive
%			g cm^{-3}	g C m^{-2}					
66.2	20.6	13.1%	1.2	107	1575	1897	10	20	11

7.2.4 Scenario analysis using the Century model

Using the Century model several scenarios including different tillage methods from conventional to conservational practices, residue removals from 0 to 75%, fertilizer N rates from 0 to 15 g N m^{-2}, and fertilization options from single to the combined organic and inorganic fertilizer application (Table 7.5) were run to predict SOC changes as functions of management options, and further evaluate management practices for sustainable land use in the area.

Table 7.5 Management options for tillage/residue/fertilization treatments of the scenario analysis

Option A (tillage)	CT (conventional), NT (no-till), SS (subsoiling), DP (stover-incorporated)
Option B (residue)[a)]	G0 (0% removal), G10 (10% removal), G50 (50% removal), G75 (75% removal)
Option C (N rate)[b)]	N0 (0 g N m^{-2}), N5 (5 g N m^{-2}), N10 (10 g N m^{-2}), N15 (15 g N m^{-2})
Option D (fertilization)	CK (G75), F (fertilizer, 10 g N m^{-2}), M (manure, 60 g C m^{-2}), S (stover, 90% return), MF (M + F), SF (S + F), SFM (S + F + M)

[a)]Combined with N10; [b)]Combined with G10.

Using the site-specific data and the field data from the experiments on residue/fertilizer management the SOC changes were simulated with a run-time scale of 15 years (1990-2005). The simulated results were obtained by comparing model output with observations from 1992 to 2002 and making appropriate adjustments to parameter values to achieve a close fit between model output and measured values.

The agreement between measured (Xobs) and simulated (Xmod) SOC values for each one of 12 treatments was assessed through linear regression analysis and correlation analysis. The linear regression equation of the model values on the corresponding field data was:

$$X_{\mathrm{mod}}(i) = a + bX_{\mathrm{obs}}(i) \quad (1)$$

where *i* (*i* =1, … , *n*) is the year of SOC measurement during periods of 1992 to 2002 for each treatment, and a and b are coefficients. The mean difference (*MD*) between simulated values and measured data was estimated as described below (Smith et al., 1996; Gilmanov et al., 1997):

$$MD = \frac{1}{n}\sum_{i=1}^{n}\left(X_{\mathrm{mod}}(i) - X_{\mathrm{obs}}(i)\right) \quad (2)$$

7.3 Results and discussion

7.3.1 Model testing and validation

The comparison of simulated SOC to measured SOC in the treatments with different amounts of residue/manure/fertilizer application (Table 7.6) showed that the model showed that the model fit was better during the experimental periods from 1995 to 2002 than the period from 1992 to 2002. Higher coefficients were found between the simulated results and measured data from 1995 to 2002 (r = 0.53**), n = 64, *MD* = 31 g m-2) than those from 1992 to 2002 (r = 0.34**, n = 132, *MD* = 16 g m^{-2}).

Results of the correlation analysis showed that there was better agreement between simulations and measurements from experiments treated with high fertilization of inorganic fertilizer, stover, and manure combined (Treatments 6, 7 and 9) (Table 7.6). However, the model was not a good predictor with data from Treatments 2, 3, 10, and 12 (control) because the simulated results were underestimated, probably due to the extreme C/N ratios of organic materials added with the highest value of 69 for Treatment 2, and the lowest value of 22 for Treatment 10, and the extreme N deficiencies for Treatments 12 and 3. The high mean differences between the measured and simulated values (*MD* = 112-161 g m^{-2} for 1995-2002 were found for Treatments 1, 9, and 11 with high manure and stover C input, for which the simulated results were overestimated and the errors of the model were 2.9% to 4.3% of the maximum of the observations. The error of the model was only 0.7% of the maximum of the observations for the whole 8 year long period from 1995 to 2002, ranging from -2.2% to 4.3% of the maximum values observed from each treatment during the period 1995-2002 (Table 7.6). Some uncertainties in the model affecting soil carbon turnover might result from variations in weather, and changes in management parameters, including changes in organic C and N, and inorganic N inputs, which influenced the C/N rate, decomposition rate, humification coefficient, crop below- and above-ground production levels, and their interactions.

7.3.2 Scenario analysis using the Century model

Figure 7.1 showed the trends in SOC changes calculated through a scenario analysis of different tillage methods, residue practices, fertilizer N rates, and fertilization options. The simulated SOC increased greatly with changes in the tillage methods from the conventional tillage (CT) to the conservational tillage practices (Fig 7.1a) and with changes in residue practices from 75% to 0 residue removal (or 100% residue return) (Fig. 7.1b). The changes in fertilizer application rate from 0 to 15 g N m^{-2} caused the rate of SOC turnover to slow down (Fig. 7.1c), while improved fertilization options, such as adding stover (S) or manure (M) and especially combining organic C inputs with inorganic fertilizer (F) application (stover + manure + fertilizer) revealed increases in SOC over time (Fig. 1d). This was due to the adjusted C/N ratio of the organic amendments with addition of inorganic N to the residue- or manure-incorporated soils.

The regression analysis showed a close relationship between annual C inputs to soil and the rate of C sequestration in the top 20 cm layer, calculated from the simulations of the 10-year field experiments with different amounts of fertilizer/residue/manure application (Fig. 2). The slope coefficient of the regression equation indicated that about 16% of the annual C input from stover/manure contributed to the C sequestration each year; the rest was released to the atmosphere as CO_2 from microbial respiration. The annual C loss from decomposition of the humic C pool for the soil without C input (x = 0) was about 0.2 t C ha^{-1} $year^{-1}$, indicating that the annual input C was about 1.3 t C (0.1987/0.1566 = 1.27) ha^{-1} $year^{-1}$, being equivalent to about 50% residue return needed to maintain SOC balance against respiration in this soil.

Table 7.6 The correlation coefficients (*r*) and mean difference (*MD*) estimated between the simulated and measured data during periods of 1992-2002 and 1995-2002 for the 12 treatments

Treatment	Fertilizer N	Stover	Manure	Organic C/N added	1992–2002		1995–2002		Error[a)] (1995–2002)
					r ($n = 11$)	*MD*	r ($n = 8$)	*MD*	
	kg ha^{-1}					g m^{-2}		g m^{-2}	%
1	105	3 000	6 000	34	−0.10	0.3	0.53	112	2.85
2	105	3 000	0	69	0.40	63.0	0.26	51	1.31
3	31	879	4 500	27	−0.16	42.0	−0.82	20	0.51
4	179	879	4 500	27	0.32	0.6	0.61*	34	0.82
5	31	5 121	4 500	42	0.56*	32.0	0.77**	52	1.29
6	179	5 121	4 500	42	0.65**	7.0	0.89***	38	0.87
7	210	3 000	4 500	49	0.66**	27.0	0.70**	19	0.46
8	0	3 000	4 500	49	0.06	111.0	0.59*	−22	−0.53
9	105	6 000	1 500	56	0.64**	139.0	0.65*	161	4.26
10	105	0	1 500	22	0.22	15.0	0.20	−45	−1.16
11	105	3 000	3 000	41	0.44	73.0	0.66*	114	2.87
12	0	0	0	0	−0.17	68.0	−0.74	−79	−2.17

*, **, ***Significant at the 0.1, 0.05, and 0.01 levels, respectively. [a)] Error (%) = 100 × MD/maximum X_{obs}, where X_{obs} is the measured SOC.

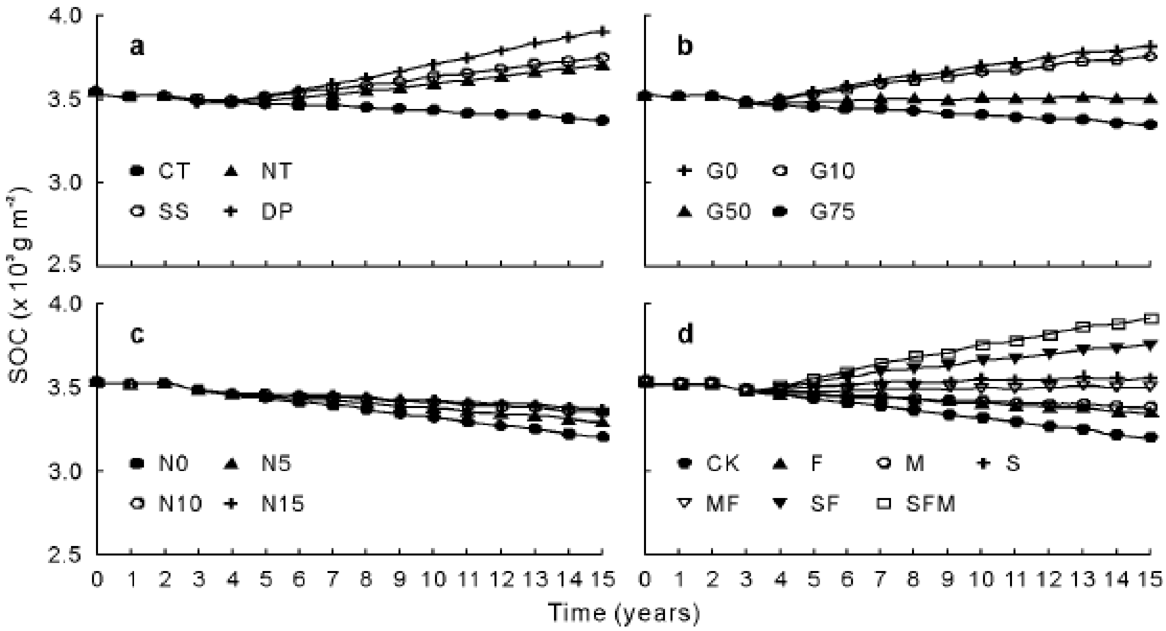

Fig. 7.1 Dynamic changes in SOC calculated through scenario analysis using the Century model with different tillage (CT, conventional; NT, no-till; SS, subsoiling; DP, stover-incorporated) (a), residue (G0, 0% removal; G10, 10% removal; G50, 50% removal; G75, 75% removal) at N10 (b), fertilizer N rate (N0, 0 g N m^{-2}; N5, 5 g N m^{-2}; N10, 10 g N m^{-2}; N15, 15 g N m^{-2}) with G75 (c), and fertilization (CK, G75; F, fertilizer of 10 g N m^{-2}; M , manure of 60 g C m^{-2}; S, stover of 90% return; MF, M+ F, SF, S + F; SFM, S + F + M) (d) management options.

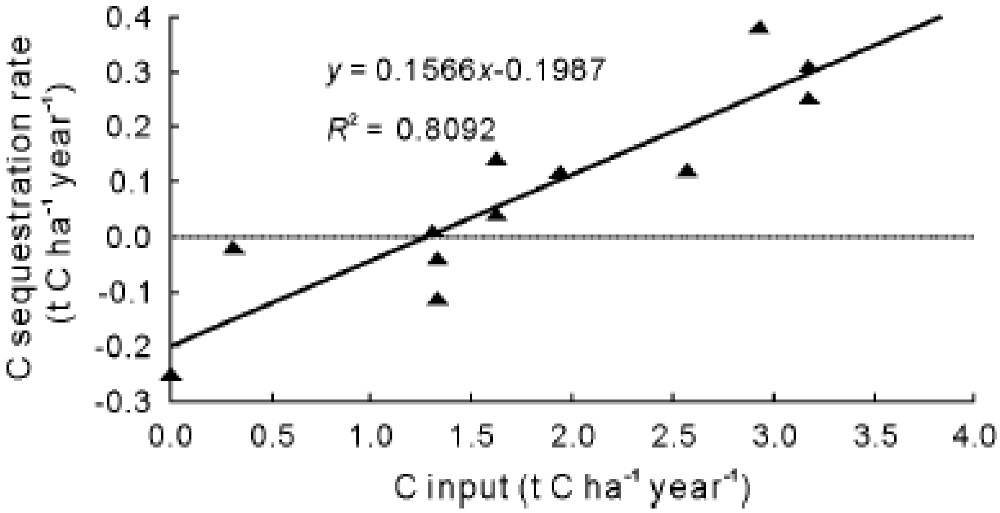

Fig. 7.2 Relationship between the rate of C sequestration and the annual C inputs (from stover/manure) to the soil in the top 20 cm layer.

The rates of C sequestration were influenced by management options, as shown in Fig. 7.3. With changes in tillage methods (Fig. 7.3a) from conventional (CT) to conservation practices the rate of C sequestration (t C ha^{-1} $year^{-1}$) increased from -0.111 with CT to 0.117-0.268 with conservation tillage practices (0.117 with NT (no-till), 0.160 with SS (subsoiling) and 0.268 with DP (stover incorporation).

With changes in residue removals (Fig. 7.3b) from 0 to 75%, the rate of C sequestration decreased from 0.227 to -0.138 t C ha^{-1} $year^{-1}$ when combined with inorganic N (N10), and from 0.069 to -0.254 t C ha^{-1} year-1 when applied without N (N0). Thus, returning at least 50% residue to the soil showed the potential to sequestrate C or maintain SOC level. With the increase in N rates (Fig. 7.3c) from 0 to 15 g N m^{-2} the rate of SOC loss decreased from 0.254 to 0.123 t C ha^{-1} $year^{-1}$ with 75% residue removal, while the rate of C sequestration increased from 0.027 to 0.198 with 10% residue removal. Meanwhile, with M (manure amendment) and with MF (manure + fertilizer) the rate of SOC loss decreased to 0.118 and 0.021 t C ha^{-1} year-1, respectively, compared to 0.254 t C ha^{-1} $year^{-1}$ with the control (Fig. 7.3d). Returning residues to the soil, especially combined with application of organic and/or inorganic fertilizers, caused an increase in the rate of C sequestration, being about 0.027, 0.179, and 0.299 t C ha^{-1} $year^{-1}$ with S (stover), SF (stover + fertilizer) and SFM (stover + fertilizer + manure), respectively. Thus, manure amendment could enhance SOC in small crop-livestock systems in which crop residue land application was limited. Similarly, the long-term experiment at Rothamsted, U.K., has documented continuous increases in SOC content even after 150 years of manure application at the rate of 35 Mg ha^{-1} $year^{-1}$ (Powlson et al., 1998).

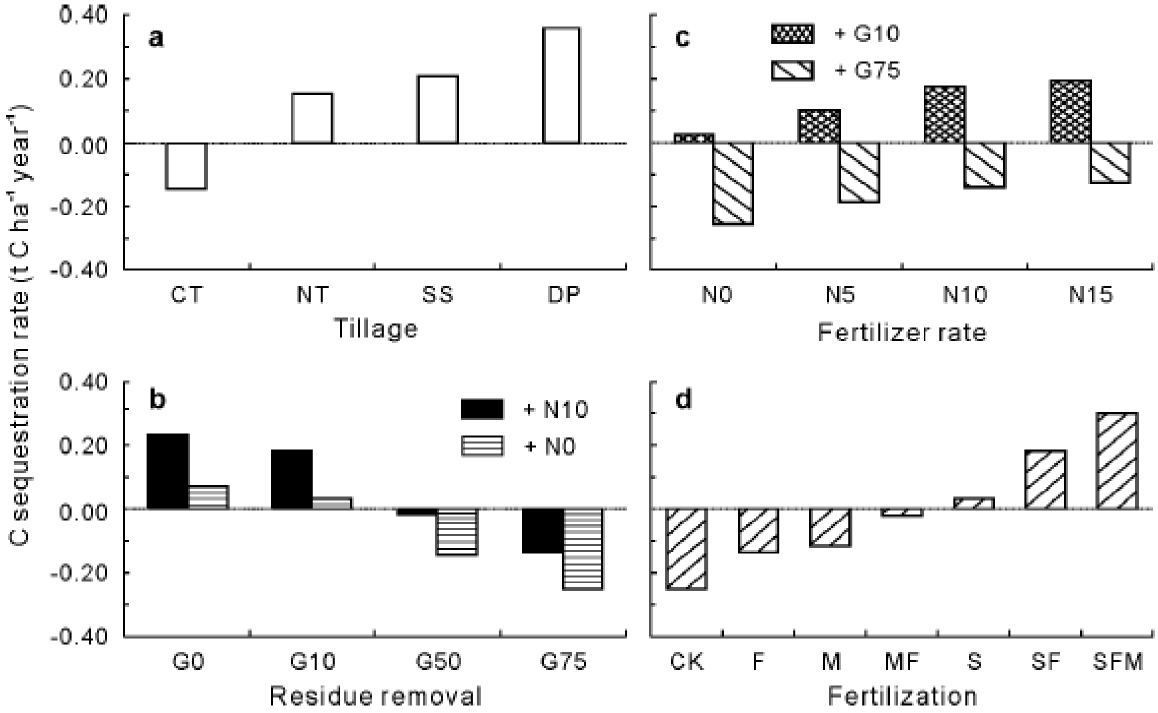

Fig. 7.3 Effects of different tillage (CT, conventional; NT, no-till; SS, subsoiling; DP, stover-incorporated) (a), residue (G0, 0% removal; G10, 10% removal; G50, 50% removal; G75, 75% removal) (b), fertilizer N rate (N0, 0 g N m^{-2}; N5, 5 g N m^{-2}; N10, 10 g N m^{-2}; N15, 15 g N m^{-2}) (c), and fertilization (CK, G75; F, fertilizer of 10 g N m^{-2}; M , manure of 60 g C m^{-2}; S, stover of 90% return; MF, M+ F, SF, S + F; SFM, S + F + M) (d) management options on C sequestration in the top 20 cm soil layer.

7.4 Conclusions

The Century model was used to simulate SOC dynamics linked with measurement data from 10-year field experiments to evaluate residue/manure and inorganic fertilizer application for dryland maize production systems of northern China. The model was able to simulate trends in SOC and explore long-term soil C cycling processes related to soil conservation tillage and fertilizer management practices under dryland soil-crop management systems. There was a close agreement between simulations and measurements with appropriate applications of stover, manure and inorganic fertilizer combined. However, the model did not predict the SOC dynamics with extreme C/N ratios from added organic materials very well, as the simulated results were underestimated. However, the error of the model was only 0.7% of the maximum for the whole 8 year long period of observations from 1995 to 2002. A scenario analysis using the Century model provided much valuable information to better understand the impacts of different management options on long-term SOC dynamics. Scenarios of changed tillage methods, changed residue practices especially when combined with inorganic fertilizer N application, and changed fertilization options showed potential to maintain and enhance SOC in the long run. Meanwhile, increased inorganic N rate caused SOC turnover rate to slow, but not to have a net C sink without any organic C input, while residue returned to the land (at least 50%) was the best way to cause a net C sink. The Century model simulation showed a good relationship between annual C inputs to soil and the rate of C sequestration in the top 20 cm layer which provided quantitative estimations of changes in parameters crucial for sustainable land use and management. It was recommended that conservation tillage practices for sustainable land use be integrated by combining conservation tillage/residue management with appreciable organic and inorganic fertilizer application, adapted according to the local residue resource, soil fertility and production conditions. At least 50% residue return into the soil was needed annually for maintenance of SOC balance, and manure amendment was important for enhancement of SOC in small crop-livestock systems in which crop residue land application was limited.

8 General discussion

8.1 Introductory remarks

This thesis reports on the outcome of research on conservation farming in drylands of northern China. It is based on long-term field studies and related research. The general objective of the study was "*to improve the understanding of the interactions between conservation tillage and nutrient management in dryland farming systems in northern China*". The specific objectives were:
1. to provide an overview of the need for and perspectives of conservation tillage;
2. to assess the effects of rainfall on crop yields and water use, as function of tillage and nutrient management practices;
3. to assess the effects of combined applications of crop residue, cattle manure and fertilizer on crop yield, nutrient and water use efficiencies, nutrient balances and soil fertility indices, under conditions of reduced tillage;
4. to assess the effects of tillage, residue, and fertilization management on soil organic matter dynamics.

This chapter attempts to provide an overall synthesis of the work done, and to give an indication of how the research findings have contributed to a better understanding of the problems, to solving these problems, and to progressing science.

8.2 Discussion

8.2.1 Need for conservation

China's agriculture is extremely diverse. The country has an ages old farming history and from the beginning, organic fertilizers (such as green manure, animal manure, night soil, crop residues) were used in traditional farming. In northern China, farmers have experience in using methods to alleviate the effects of drought on non-irrigated crop production. Examples of these traditional methods are *'sand covering cultivation', 'furrow-seeding or square-pit methods' 'ridge cultivation'* , and *'direct sowing in the stubble field'* (Liu and Mou, 1988; Xin et al., 2002; Li, 2004). On the other hand, unfortunately, traditional farming practices also include poor soil management with intensive ploughing, residue removal or burning, low nutrient input, and also shifting cultivation practices in some hilly areas of northern China (Li, 2004). These practices have contributed to soil degradation by erosion, leading to a decline in soil fertility and soil quality (Lal, 2004b).

Increasing food demands by the rapidly growing population accelerated the development of farm mechanization and use of chemical fertilizers in large areas of

China. This has resulted in large increases in yields per unit of land and labour during the last decades. The traditional farming practices based on organic fertilizers began to be replaced by practices based on chemical fertilizers. From the early 1980s, chemical fertilizers dominated the total nutrient supply to agricultural lands (Wang et al., 1996; Lin, 1998). Excessive and unbalanced fertilization has led to increasing nutrient concentrations in surface and ground water, sometimes aggravated by dumping animal wastes (Zhu, 2002). However, agriculture in many dryland regions can be still characterized by mining of soil nutrient pools. Hence, the diversity in nutrient management practices is also wide.

Currently, agriculture in China faces a multitude of threats, as follows from these examples:

- Increasing fertilizer consumption and associated effects. The average fertilizer use was 235 kg ha^{-1} in the late 1990's (FAO, 1999), which is one of the highest in the world. There is also a large regional diversity of fertilizer use, ranging from 80 to 840 kg ha^{-1} (National Bureau of Statistics of China, 2003).
- Decreasing water resources: The total volume of surface water and groundwater resources is 2,800 billion m^3 (the sixth largest in the world), but this volume is rapidly decreasing because water use is larger than water resource replenishment. The water resource per capita (2,245 m^3) is only one-third of the world's average. In that respect, China is among the most water-deficient countries in the world (Li and Wang, 2000).
- Increasing water erosion. Per year, 1.6 billion tons of soil washes into the Yellow River from China's Loess Plateau, which has the highest rate of water erosion in the world (Science, 2004). Thirty-seven percent of China's land territory is affected by water erosion (MWR, 2002).
- Increasing dust storm erosion: The expansion of deserts at 3600 km^2 a year due to farming and (over)grazing stokes the country's (in)famous dust storms. Degradation endangers more than 27% of China's land territory (Dregne, 2002) or 79% of the dryland area. It comprises 7.4% of the world's total.
- Increasing emissions of greenhouse gases. China is listed as number 1 in the world, in terms of greenhouse gas emissions from agriculture. China is one of the largest energy consumers at 11% of the world's total, generating 15% of global emissions (Baumert et al., 2005).

Conservation farming may contribute to minimizing the environmental degradation in current agriculture. The integration of conservation tillage and improved nutrient management practices may help in increasing nutrient and water use efficiencies, decreasing water and wind erosion and decreasing energy use and increasing carbon sequestration in soil. This is schematically shown in Fig. 8.1. An improvement of soil fertility and quality with "response management practices" will increase water and nutrient use efficiencies. Traditional conservation farming practices based on organic manure use and reduced tillage methods should be

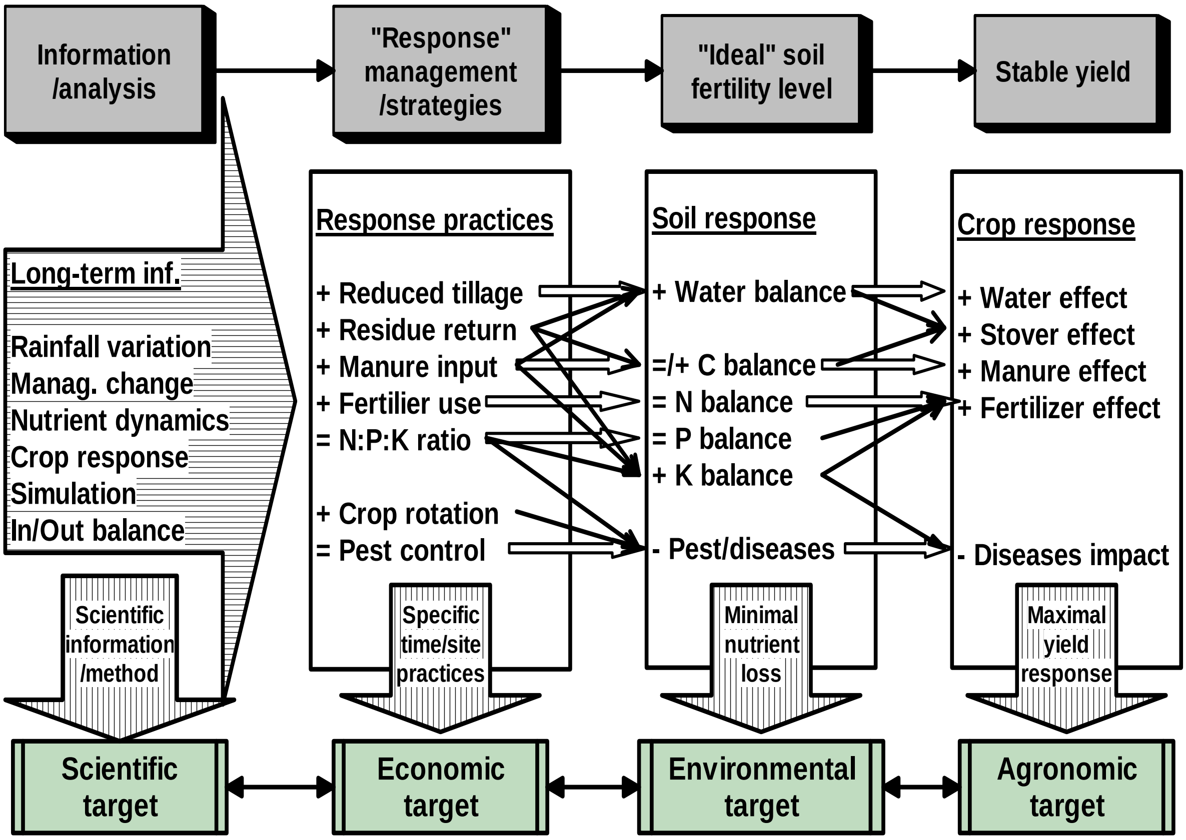

Fig. 8.1 “Response” nutrient management for dryland farming

reconsidered in the current context, and may be still applicable, perhaps with small modifications. Careful application of such systems may contribute to (re)building soil fertility, save energy and fertilizer, and protect soil from erosion in a better way than “modern” farming.

8.2.2 Conservation tillage and soil organic carbon

Soil quality is defined as “the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, to maintain or enhance water and air quality, and to support human health and habitation” (Karlen et al., 1997). Long term studies have shown that soil organic carbon (SOC) is the most important indicator of soil quality and agronomic sustainability, because of its impact on other physical (such as bulk density, Ksat, soil structure, water capacity), chemical (such as pH, EC, nutrient availability) and biological properties (such as potentially mineralizable N, soil respiration). SOC is important in China: the country stores about 12% of the global SOC pool. It has been estimated that its potential of soil C sequestration can offset about 25% of the annual fossil fuel emissions in China (Lal, 2004b), though such estimations include many assumptions and uncertainties. In the dryland farming areas of northern China, soil quality degradation associated with over-tillage, crop residue removal and burning has become a severe problem. Soils have lost up to 50% or more of the antecedent SOC pool, and erosion has decreased SOC levels from 1.6 to 0.65% in northern China over a 50-year period (1930s to 1980s) according to a review by Lal (2004).

Our studies showed that the annual losses of organic C and N range from 53 to 1044 kg ha^{-1} and 5 to 90 kg ha^{-1}, respectively, per cm of topsoil removed from farm land through duststorms. Our studies also indicate that soil losses by wind erosion can be reduced by up to 79% when farmers shift from conventional soil tillage methods to no-till and conservation tillage (Wang et al., 2006).

The increase in soil C, though, is a slow process and it may take 5-10 years, depending on moisture conditions and management practices, before effects become noticeable. This slow and delayed effect is related to high soil organic matter mineralization (up to 4 %; Cai, 1996), which is affected by the quantity and quality of annual C input and mineral N added and the temperature and rainfall.

Simulation modelling, using the Century model and data of the field experiments, gave the following relationship between annual C inputs (Cin) to soil and the rate of C sequestration (CSR) for the top 20 cm layer:

$$\text{CSR (t C ha}^{-1}\text{yr}^{-1}) = 0.16\text{Cin} - 0.2 \qquad (R^2 = 0.81)$$

This equation suggests that about 16% of the annual C input from stover and/or manure contributed to the C sequestration each year. Without C input there is a loss of about 0.2 t C $ha^{-1}y^{-1}$ caused by decomposition of the SOC pool. Thus, this suggests that about 1.3 t C $ha^{-1}yr^{-1}$, equivalent to about 50% of the residue needs to be returned to maintain a stable SOC content. The same analysis showed that the rate of C sequestration changed from negative under conventional, to positive under conservational practices. There was also a positive effect on CSR under no-till. This is in accordance with results of Canadian long-term studies (VandenBygaart et al., 2003). Lal (2004) predicted an increase of the CSR (0.2 to 0.3 t $ha^{-1}yr^{-1}$) with adoption of Recommended Management Practices for cropland (returning crop residues to soil; improving nutrient cycling and soil fertility through integrated nutrient management strategies; and adopting conservation tillage practices. However, such modelling estimates need to be tested in practice before any extrapolation can be made. The long-term field experiments described in chapters 5 and 6 indicate indeed that SOC increases when inputs of effective C increase, but the measured rate of change in SOC were smaller than predicted on the basis of simple model calculations.

Our studies show that conservation tillage practices can either be completely refraining from mechanical disturbance of the soil as is the case in the no-till system where sowing is done with a special sowing machine, or applying a rather deep tillage operation in the form of deep ploughing or subsoiling. In the latter system, the reduction is in the number of operations (only one immediately after harvest vs. several in the conventional system). The beneficial effects of reduced tillage are increased water storage, and reduced evaporation.

Crop residue, when used in combination with reduced tillage operation or no-till increased yields and reduced evaporation losses. This was particularly true in the wheat production systems, and to a lesser degree in spring maize. In situations with low spring temperatures, residue should be incorporated into the soil in autumn, to circumvent delayed emergence of maize seedlings.

Conservation tillage, combined with residue application led to improvements in soil physical conditions, (better water conservation and soil protection from wind erosion), soil water storage, and crop yields, and thereby to a higher water use and water use efficiency.

8.2.3 Conservation tillage and nutrient management

Conservation tillage practices affect soil physical conditions and soil water and carbon storages, and thereby nutrient dynamics in soil and crop yields. As a consequence, conservation tillage practices and nutrient management strategies must be intimately related. This is especially the case when reduced tillage practices necessitate the application and incorporation of fertilizers and organic residues into the soil long before the actual growing season of spring maize starts. This practice strongly decreases wind erosion in spring but may contribute to increased nutrient losses through leaching and denitrification before the growing season. The results of our long-term field experiments indicate that the responses of crop yield and nutrient uptake to the fall applied fertilizers and organic residues were relatively large, suggesting that nutrient losses through leaching and denitrification were relatively small. Such small nutrient losses during the winter half year are related to the dry and cold weather during the winter half year, but possibly also to the immobilization of N and P in organic biomass. The C:N and C:P ratios of root + stubble and stover of maize are high, and available N and P from soil or fertilizers are needed for the decomposition of these crop residues in the soil. In a later stage, possibly during the growing season, the initially immobilized N and P may become available again after the mineralization of the microbial biomass. This would suggest that the practice of applying stover and fertilizer in autumn initiates a nutrient dynamics in the soil which is synchronized to the uptake pattern of maize. Though leaching and denitrification losses seem to be small during the winter half year, the basal N fertilizer application should be modest, for two reasons: (i) the basal N application should not be based on potential yields but on (average) water-limited yields, and (ii) N losses will occur when off-season rainfall is relatively high. The combination of a modest basal application with a top dressing during the early growing season when crop demand is high has not been tested in this study. However, studies elsewhere have shown that such response nutrient management practice (see Fig. 8.1) might contribute to high crop yields and high nutrient use efficiencies. Evidently, the potential and feasibility of such practice in the dryland area of northern China should be tested first before any recommendation can be made to practice.

Our long-term field experiments with various combinations of organic residues and NP fertilizer applied to spring maize under reduced tillage conditions show that the organic residues were effective in supplying K to the crop. This holds especially for stover but also for the cattle manure. Soil conservation practices which include residue mulching and return to the field of crop residues and animal manure are effective in supplying all essential nutrients, which is not the case with straight NP fertilizers. The long-term field experiment with spring maize in Shouyang has shown that K deficiency increases over time, but also that the soil has a high buffer capacity. However, continuous depletion of soil K will ultimately diminish this capacity and will lead to declining crop yields, irrespective of the NP fertilizer input and reduced tillage practices. Soil chemical studies are needed to assess the kinetics of the soil K pools and to predict the elapse of the K supplying capacity of the soils in the dryland areas of northern China.

Conservation tillage combined with residue application also had large effects on nutrient balances and soil fertility indices. The nutrient balances were instrumental in explaining the effects of the various treatments in the long-term field experiments, in terms of both crop yields and changes in soil fertility indices. Our studies clearly show the beneficial effects of applying modest amounts of manure and crop residues on extractable soil P and K. This priming effect creates an additional effect of conservation tillage practices, and indicates again the intimate relationships between tillage, residue and nutrient management.

8.3 Conclusions

Conservation farming in China is given considerable attention as a way of dealing with environmental problems caused by fertilizer overuse and erosion-induced soil degradation. Strong arguments can be found to bring traditional local conservation farming practices up-to-date. A site-specific combination of organic manure use and reduced tillage methods would be beneficial in terms of building soil fertility, and saving energy and fertilizer use. It would protect soil from erosion caused by so-called “modern” mechanized farming systems.

Our studies indicate that soil losses by wind erosion can be reduced by up to 79% when farmers shift from conventional soil tillage methods to no-till. With a balanced combination of organic and inorganic fertilizer, soil organic carbon showed a slow increase in time. On average at least 50% of the crop residue should be returned in the soil to maintain acceptable organic carbon levels, depending also on crop yields.

Manure and stover supplied effective carbon and essential nutrients, and thereby had positive effects on C and N, P and K balances. These organic residues also contributed to increasing the water use efficiency.

Low growing season rainfall (during April to October, but especially in the month of July) causes low maize grain yields. During subsequent dry years the decrease in yields was aggravated by diseases. The increased incidence of diseases may also be related to increased K and micronutrient deficiencies. Future research on soil conservation management strategies should therefore also consider these aspects.

This study has increased the understanding of the complex interactions between soil, crop residue and nutrient management in China’s dryland farming systems. It has also shown that the research questions can only be solved meaningfully using an integrated approach. Such an approach should not only be applied in the field experiments, where agronomic, technical and soil-related parameters must be considered, the integration should also take shape in combining (long-term) field work with modelling and careful collection of climatic data.

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Summary

Introduction

China has a large area of dryland in the North, which accounts for over 50% of the nation's total land area, covering 17 provinces. About 22% of the total population live here. Maize and wheat are the main cereals grown in the dryland area, accounting for 28% of the nation’s cereal production. Dryland farming is playing an important role in the production of China’s food supply, and yet, these regions are the most poorly developed ones in China.

Crop production in the dryland areas of China is constrained by adverse weather (with low and highly variable rainfall), topography (hilly landscapes), erosion, and low fertility soils with low soil organic matter (SOM) and nutrient contents. There is a high risk for very low production levels or even crop failure, particularly under poor management, including excessive cultivation, overgrazing and the routine removal of crop residues. The problems are getting worse with increased land degradation.

Land degradation affects around 2.6 million km^2 of a total of 3.3 million km^2 of drylands (excluding the extremely arid areas), accounting for over 27% of China's land territory or 79% of the dryland area. It threatens the productivity of agricultural soils in these areas, due to the loss of topsoil with valuable nutrients and organic matter. Thus, soil conservation and fertility restoration in the regions have been given great considerations.

Conservation tillage research started in the 1980’s, via a large number of national and international research projects. The Chinese government has been actively involved in the demonstration and extension of conservation tillage practices from 2002 onwards, following the recognition of the environmental impacts of sand and dust storms, wind erosion, water erosion, and land degradation. The current area under conservation tillage only accounts for 0.2% of the area worldwide, only about 0.1% of China’s total arable land area. This area is far below what would be needed in view of the degradation of the land resource and soil quality. Therefore, strengthening research on conservation tillage and water, nutrient, organic carbon, and energy saving technologies is important.

Problem definition and objectives of the study

The slow acceptance and adoption of conservation tillage in practice may in part be attributed to conceptual, scientific, and technological reasons and to the regional diversity in conditions. There seems to be a lack of mechanistic understanding of site-specific success factors for implementation of conservation tillage in dryland areas. There is also a lack of knowledge about the possible side-effects of conservation tillage. What is needed? (1) A better understanding of possible interactions between conservation tillage and variations in weather on crop yield and environmental impact; (2) More knowledge of the long-term impacts of tillage practices on nutrient balances, soil fertility and crop production.

The general objective of this PhD study is to improve the understanding of the interactions between conservation tillage and nutrient management in dryland farming systems in northern China. Specific objectives are:

1. to provide an overview of the need for and perspectives of conservation tillage;
2. to assess the effects of rainfall on crop yields and water use, as function of tillage and nutrient management practices;
3. to assess the effects of combined applications of crop residue, cattle manure and fertilizer on crop yield, nutrient and water use efficiencies, nutrient balances and soil fertility indices, under conditions of reduced tillage;
4. to assess the effects of tillage, residue, and fertilization management on soil organic matter dynamics.

The study comprised literature reviews, long-term field experiments and simulation modelling. Literature was analysed, focussing on conservation tillage (in China and on a global scale), and on dust storm erosion in northern China. The field experiments involved various tillage and residue and nutrient management practices. A scenario analysis using the Century model aimed at forecasting the effects of management on soil organic carbon dynamics and potential carbon sequestration. Field research was conducted at 4 sites in the dry semi-humid region of northern China. Sites are in Tunliu, Linfen and Shouyang counties of Shanxi province, and in Luoyang of Henan province. These sites are located between 111°N and 113°N, and between 34°E and 38°E.

Summary of the major findings

Potential effects of conservation tillage

The review of long-term conservation tillage research, revealed that there are several potential benefits associated with conservation tillage, including carbon sequestration, higher crop yields and increased water and nutrient use efficiencies. It suggested that integrated, applicable and advanced, technologies are needed to ensure successful acceptance and adoption of conservation methods in dryland farming systems in China. The study emphasized the need for better knowledge of the long-term impact of site-specific tillage practices, and the need to develop appropriate practical technologies with minimal costs.

Developments in conservation tillage

The review of conservation tillage research in dryland regions of China showed that reduced tillage practices increased crop yields and water use efficiency by up to 35%. The use of residues on the soil surface should be adjusted to local weather condition; residue incorporation is recommended if the annual average temperature is below 7°C. Options for conservation tillage (including tillage-related management practices of residue, fertilizer, crop rotation, water and pesticide) were grouped according to four dryland zones, as follows: 1) North-west desert with serious wind erosion and desertification: no-till fallow, keeping stubble cover and adding organic /inorganic fertilizers; 2) Loess plateau with serious water erosion: growing cover crops, keeping stubble surface cover combined with contour/strip cropping; 3) North-east cold region: reduced till /ridge-till and keeping high stubble cover; and 4) North China Plain region: crop residue conservation, no-till sowing in mulch and balanced fertilizer application.

Dust storm erosion and its impact on soil carbon and nitrogen losses

A desk study revealed the cause – effect relationships of dust storms-related soil erosion and nutrient losses in northern China. It showed that nutrient losses by dust storm erosion in northern China are considerable, and related to increased soil cultivation and conventional tillage practices. The assessment showed that the annual losses per cm topsoil of soil C and N by dust storm erosion in northern China range from 53 to 1044 kg ha^{-1} and 5 to 90 kg ha^{-1}, respectively. Field studies suggest that soil losses by wind erosion can be reduced by up to 79% when farmers shift from conventional soil tillage methods to no-till.

Effects of variation in rainfall on rainfed crop yield

Crop production in the dryland farming areas of northern China is constrained by low and variable rainfall. This chapter provides a detailed analysis of the relationships between the variation in monthly-seasonal-annual amounts of rainfall and yields of rainfed wheat and maize. The analysis is based on data from long-term field experiments carried out in dryland farming research projects in Tunliu, Linfen, Shouyang and Luoyang. Yields of maize and wheat were highly related to the rainfall distribution. For wheat, linear relations were found between grain yield (GY) and annual rainfall (AR), and between GY and soil water at sowing (SWS). Spring maize GY in Shouyang was sensitive to June, July, and April rainfall. The results indicate that possible options to alleviate occurring moisture stress for crops must be tailored to the rainfall pattern. This holds especially for tillage and farming systems and practices that aim at enhancing soil and water conservation.

Tillage and residue effects on rainfed wheat and maize production

Field studies on tillage and residue management for winter wheat and spring maize were conducted at 4 sites in Shanxi and Henan provinces in the dry semi-humid regions of northern China. The effects of different tillage and residue application methods on soil physical conditions, soil water storage, water use, crop yields, and water use efficiency were assessed. Conservation tillage with residue application practices showed various benefits. The changes in soil bulk density improved water conservation and gave protection of the soil from wind erosion. Conservation tillage improved water availability to crops, caused by increasing water storage and reducing water loss during the summer fallow or rainy season. Conservation tillage practices increased crop yields in general. Reduced tillage gave yields around 22%

higher in spring maize and round 7% higher for winter wheat. Yields under no-till were very close to those from conventional methods.

Long-Term effects of crop residue, manure and fertilizer on dryland maize

A long-term experiment was carried out in the dryland of northern China to assess the effects of applications of maize stover, cattle manure and NP fertilizer on maize yield and nutrient use efficiencies, nutrient balances and soil fertility in a spring maize cropping system, under reduced tillage conditions. The ongoing factorial field trial was conducted at Shouyang Dryland Farming Experimental Station from 1993 onwards.

Results of the field experiments indicated that the observed decline in crop yields over time were related to changes in total rainfall and its distribution over the growing season, but also to depletion of the soil potassium (K) reserve. Balanced combinations of stover, manure and NP fertilizer gave the highest yield, nitrogen recovery efficiency (NRE), and water use efficiency (WUE). Reduced tillage with adding stover and manure in autumn prior to ploughing is effective in minimizing labor requirement and wind erosion. The potentials of split applications of N fertilizer, targeted to the need of the growing crop (response farming), should be explored to further increase the N use efficiency.

Statistical analyses using multiple regression models showed that the partial N, P and K balances were strongly influenced by annual variations in the amounts of soil water at seeding (SWS) and growing season rainfall (GSR). The analysis of nutrient balances and soil fertility indices revealed that nutrient inputs in most treatments were far from balanced. It is concluded that the concepts of 'ideal soil fertility level' and 'response nutrient management' provide practical concepts for improving nutrient management under the variable rainfall conditions of dry land areas. Returning crop residues and manure to the soil was highly effective in restoring negative K and C balances.

Scenario analysis of tillage, residue and fertilization effects on SOC dynamics

Based on data from 10 years of field experiments, scenarios analysis using the Century model was conducted to forecast the effects of management on soil organic carbon (SOC) dynamics. The following suggestions are given: 1) with conservation tillage practices on average at least 50% (equivalent to 1.3 t C) of the crop residue should be returned in the soil to maintain acceptable organic carbon levels annually. 2) Increasing inorganic N slowed down the SOC turnover rate but did not create a net C sink without any organic C input (crop residue or animal manure).

Synthesis

Conservation farming in China is given considerable attention as a way of dealing with environmental problems caused by fertilizer overuse and erosion-induced soil degradation. Strong arguments can be found to bring traditional local conservation farming practices up-to-date. A site-specific combination of organic manure use and reduced tillage methods would be beneficial in terms of building soil fertility, and saving energy and fertilizer use. It would protect soil from erosion caused by so-called “modern” mechanized farming systems.

Our studies indicate that soil losses by wind erosion can be reduced by up to 79% when farmers shift from conventional soil tillage methods to no-till. With a balanced combination of organic and inorganic fertilizer, soil organic carbon showed a slow increase in time. On average at least 50% of the crop residue should be returned in the soil to maintain acceptable organic carbon levels, depending also on crop yields. Manure and stover supplied effective carbon and essential nutrients, and thereby had positive effects on C and N, P and K balances. These organic residues also contributed to increasing the water use efficiency.

This study has increased the understanding of the complex interactions between soil, crop residue and nutrient management in China’s dryland farming systems. It has also shown that the research questions can only be solved meaningfully using an integrated approach. Such an approach should not only be applied in the field experiments, where agronomic, technical and soil-related parameters must be considered, the integration should also take shape in combining (long-term) field work with modelling and careful collection of climatic data.

Samenvatting

Introductie

Het noorden van China heeft een groot areaal aan droogtegevoelige gebieden (‘dryland’). Dit gebied omvat meer dan 50 % van het nationale landbouwareaal en ligt verspreid over 17 provincies. Ongeveer 22 % van de totale bevolking woont en werkt in dit gebied. Maïs en tarwe zijn daar de belangrijkste gewassen en ze leveren 28 % van de nationale graanproductie. Niet geïrrigeerde landbouw in een droog klimaat, ook wel dryland farming genoemd, speelt een belangrijke rol in China’s voedselvoorziening, maar toch behoren de gebieden waar dit wordt toegepast tot de minst ontwikkelde en minst welvarende streken van China. De gewasproductie in deze droge gebieden wordt geremd door diverse factoren, zoals het weer (de weinige neerslag valt veelal in plensbuien), de topografie (heuvelachtig), de erosie (door water en wind) en de bodemvruchtbaarheid (laag gehalte aan organische stof en nutriënten). Het risico van een lage gewasproductie of zelfs totale mislukking van de gewasproductie is groot, speciaal in geval van slecht beheer en management. Dit risico wordt steeds groter door de toenemende bodemdegradatie. Het areaal waar deze problematiek betrekking op heeft beslaat nu al ca. 2.6 miljoen km^2, zijnde 79 % van het totaal aan dryland-areaal en daarmee meer dan 27 % van China’s grondgebied.

Om deze problemen te keren, is er in deze streken een toenemende aandacht voor (fysische) bodemconservering en herstel van (chemische) bodemvruchtbaarheid. Onderzoek naar beschermende grondbewerking (conservation tillage, CT) startte in de jaren tachtig van de vorige eeuw via een groot aantal nationale en internationale onderzoeksprojecten. De Chinese overheid is vervolgens vanaf het jaar 2002 actief betrokken geweest bij velddemonstraties en voorlichtingsprojecten , gericht op CT. Dit na de erkenning van de kwalijke gevolgen, die zand-en stofstormen, wind-en watererosie en bodemdegradatie kunnen hebben op het milieu en de leefomgeving. Het huidige oppervlak onder CT beslaat echter slechts 0.2 % van het desbetreffende areaal en slechts 0.1 % van China’s totaal aan landbouwgrond. Dit is ver beneden dat, wat noodzakelijk zou zijn ter voorkoming van degradatie en kwaliteitsverlies van de natuurlijke hulpbron bodem. Daarom is het belangrijk, het CT onderzoek te versterken, inclusief de water- nutriënten- en organischestof-voorziening met bijbehorende energiebesparende technologiën.

Probleem formulering en doelstellingen van de studie

De trage acceptatie en toepassing van CT in de praktijk moet deels worden toegeschreven aan conceptuele, wetenschappelijke en technologische oorzaken en aan verschillen in regionale omstandigheden. Er lijkt een gebrek aan inzicht te bestaan in de plaatsspecifieke succesfactoren voor de introductie van CT in droogtegevoelige gebieden.

Er is tevens een hiaat in kennis omtrent de mogelijke neveneffecten van CT. Om dit hiaat weg te werken is het volgende nodig:

1) Een beter begrip van de mogelijke wisselwerkingen tussen CT en weersomstandigheden op de gewasopbrengst en de milieukwaliteit
2) Meer kennis van lange-termijn effecten van grondbewerkingsmaatregelen op gewasproductie, nutriëntenbalansen en bodemvruchtbaarheid.

De algemene doelstelling van het promotieonderzoek was om de wisselwerking tussen CT en nutriëntenmanagement in de landbouw onder droogtegevoelige condities beter te leren begrijpen. Specifieke doelstellingen waren:

1) een overzicht (en evaluatie) te geven van de noodzaak tot en de perspectieven voor CT;
2) de effecten vast te stellen van variaties in neerslag op de gewasopbrengst en het waterverbruik als functie van grondbewerkings-en bemestingsmaatregelen;
3) de effecten te bepalen van een gecombineerde dosering van gewasresten, dierlijke mest en kunstmest op de gewasopbrengst, de efficiëntie van bemesting en waterverbruik, de nutriëntenbalansen en de bodemvruchtbaarheid onder condities van gereduceerde (extensieve) grondbewerking; en
4) de effecten vast te stellen van het grondbewerkingssysteem en het gewasresidue-en bemestingsmanagement op de dynamiek van de organische stofhuishouding in de bodem.

De studie bestond uit literatuurstudie, veeljarige veldproeven en modelsimulaties. De literatuur werd geanalyseerd en richtte zich op CT (in China en wereldwijd) en op erosie als gevolg van stofstormen in Noord-China. De veldproeven betroffen verschillende grondbewerkings-, gewasresidue- en bemestingsmaatregelen en behandelingen. Een scenario analyse met behulp van het Century rekenmodel was gericht op de voorspelling van de effecten van het veldmanagement op de dynamiek en vastlegging van organische koolstof in de bodem. Veldproeven werden aangelegd op 4 plaatsen in de drogere (sub-humide) zone van Noord-China. De lokaties bevonden zich in gemeenten (counties) Tunlieu, Linfen en Shouyang van de Shanxi provincie en in Luoyang in Henan. De proefplekken liggen tussen 111 en 113 graden Noord en tussen 34 en 38 graden Oost. Hieronder worden de belangrijkste uitkomsten samengevat.

Potentiële effecten van CT (conservation tillage)

Het overzicht van het veeljarige CT-onderzoeksprogramma maakt helder, dat er diverse potentiële voordelen te behalen zijn met CT, zoals C-opslag in de bodem, hogere gewasopbrengsten en efficiënter water- en nutriëntengebruik. Het blijkt dat geïntegreerde, toepasbare en geavanceerde technologie nodig zijn voor een succesvolle acceptatie en adoptie van bodemconserveringsmethoden. De studie benadrukte de noodzaak tot inzicht-verdiepende kennis van de lange-termijn invloed van plaats-specifieke grondbewerkingssystemen en de daaruit voortvloeiende behoefte aan passende (praktische) technologie op basis van minimale kosten.

Ontwikkelingen in CT

Het overzicht van de resultaten van het CT-onderzoek in de droge gebieden van China toonde aan, dat vermindering van grondbewerking de opbrengst en de efficiëntie van het waterverbruik tot 35% kan verhogen. Het beheer van de gewasresten dient te worden afgestemd op de lokale weerssituatie. Het inwerken in de grond van dergelijke resten wordt geadviseerd in die gevallen, waarin de gemiddelde jaarlijkse temperatuur beneden 7 graden Celcius blijft. Mogelijkheden voor CT (inclusief management van bodem, gewasresten, kunstmest, vruchtwisseling, waterhuishouding en gewasbeschermingsmiddelen) zijn gegroepeerd naar 4 klimatologische (droge) zones:

1) De Noord-westelijke woestijn met ernstige winderosie en verwoestijning: onbewerkt braakland, bedekt gehouden door stoppelresten en toevoer van organische en anorganische (minerale) meststoffen
2) Het lőss plateau, met ernstige watererosie: bodem bedekt houden met stoppelresten, gecombineerd met een teeltsysteem in rijen of stroken, die de hoogtelijnen volgen
3) De Noord-oostelijke regio: gereduceerde grondbewerking, met ruggenteelt en de bodem bedekt gehouden met stoppelresten
4) De Noord Chinese vlakte: bodembescherming door gewasresten, minimale grondbewerking en een uitgebalanceerd nutriëntenmanagement.

Stofstorm erosie en de invloed daarvan op (bodem) C en N verliezen

Een literatuurstudie onthulde de oorzaak-gevolg verbanden tussen winderosie enerzijds en de verliezen aan bodemmateriaal en nutriënten anderzijds. Het toonde aan, dat die nutriëntenverliezen aanzienlijk zijn en worden verergerd door de traditionele intensieve grondbewerking. De analyse toonde aan, dat de jaarlijkse verliezen per cm weggeblazen toplaag voor C lagen tussen 53 en 1044 kg/ha en voor N tussen 5 en 90 kg/ha. Veldstudies duiden erop, dat de verliezen aan bodemmateriaal door winderosie kunnen worden verminderd tot wel 79%, wanneer boeren omschakelen van traditionele grondbewerking naar vastegrondteelt (no-till).

Effect van neerslagschommelingen op de opbrengst van regenafhankelijke gewassen.

De gewasproductie van de dryland-teeltgebieden van Noord-China wordt belemmerd door de geringe en bovendien sterk wisselende regenval. Het onderhavige hoofdstuk geeft een gedetailleerde analyse van de verbanden tussen de maandelijkse, de seizoensgebonden en de jaarlijkse neerslaghoeveelheden enerzijds en de opbrengsten van de regenafhankelijke gewassen tarwe en maïs anderzijds. Die analyse is gebaseerd op de gegevens van veeljarige veldproeven, uitgevoerd binnen de dryland farming projecten in Tunlieu, Linfen, Shouyang en Luoyang. De opbrengsten van maïs en tarwe waren sterk gerelateerd aan de neerslagverdeling. Voor tarwe werden lineaire relaties gevonden tussen korrelopbrengst en jaarlijkse neerslag en ook tussen korrelopbrengst en bodemvochtgehalte tijdens het zaaien. De maïsopbrengst in Shouyang bleek gevoelig voor de neerslaghoeveelheid in de maanden juni, juli en april. De resultaten duiden er op, dat de mogelijkheden tot vrijwaring van optredende droogte-stress gezocht moeten worden in een optimale afstemming op het heersende regenpatroon. Dit geldt vooral voor grondbewerkings- en teeltsystemen en maatregelen, die tot doel hebben, de conservering van bodem en water te bevorderen.

Grondbewerkings- en gewasrest-effecten op regenafhankelijke productie van tarwe en maïs

Veeljarige veldproeven met betrekking tot grondbewerking en management van gewasresten van wintertarwe en maïs werden aangelegd op 4 plaatsen in de provincies Shanxi en Henan, gelegen in de droge sub-humide regio's van Noord-China. De effecten van de verschillende grondbewerkingssystemen en toedieningstechnieken op factoren als bodemfysische condities bodemvocht, waterverbruik en -efficiëntie en gewasopbrengst werden bepaald. CT had diverse voordelen. De veranderingen in bodemdichtheid verbeterden de waterconservering en beschermden de bodem beter tegen winderosie. CT verbeterde de beschikbaarheid van water voor de gewassen als gevolg van een verhoogde vochtopslag en een verminderd waterverlies gedurende de zomerbraak. CT-maatregelen verhoogden in het algemeen de gewasopbrengsten. Gereduceerde grondbewerking resulteerde in ca. 22% meer maïs en ca. 7% meer tarwe. De opbrengsten van vastegrondteelt (no-till) kwamen dicht bij die van de traditioneel bewerkte proefvelden.

Veeljarige effecten van gewasresten, mest en kunstmest op (dryland) maïs

Een veeljarig veldexperiment in een maïs teeltsysteem onder gereduceerde grondbewerkingscondities werd uitgevoerd in het droge gebied van Noord-China om de effecten van de toediening van maïsresten, dierlijke mest en NP-kunstmest vast te stellen op gewasopbrengst, nutriëntenefficiëntie, nutriëntenbalansen en bodemvruchtbaarheid. De nog lopende factoriële veldproef werd aangelegd op het Shouyang Dryland Experimental Station in 1993. Proefveldresultaten gaven aan, dat de waargenomen afname van de gewasopbrengsten in de tijd was gerelateerd aan veranderingen in totale neerslag en in de verdeling daarvan over het groeiseizoen, maar tevens aan de afname van de kaliumreserve in de bodem. Uitgebalanceerde combinaties van maïsresten, mest en NP-kunstmest gaven de hoogste opbrengst, de hoogste benutting van de toegediende N en P, en de hoogste efficiëntie van het waterverbruik (WUE). Gereduceerde grondbewerking, tezamen met toediening van maìsresten en mest in de herfst, voorafgaande aan het ploegen, is effectief in het terugdringen van de arbeidsbehoefte en de risco's van winderosie. De mogelijkheden van gedeelde N kunstmestgiften, gericht op de behoefte van het groeiende gewas (response farming) moet worden verkend, om de efficiëntie van deze N-giften verder te verhogen. Statistische analyse door middel van meervoudige regressie modellen toonde aan, dat de partiële N, P en K balansen sterk waren beïnvloed door de jaarlijkse variaties in hoeveelheid bodemvocht tijdens het zaaien en door de neerslaghoeveelheid gedurende het groeiseizoen. De analyse van de nutriëntenbalansen en de bodemvruchtbaarheid bracht aan het licht, dat de meststofgiften bij de meeste behandelingen verre van optimaal waren. Er mag worden geconcludeerd, dat de concepten van “ideale bodemvruchtbaarheid” en “meststofgift naar behoefte” goede en praktische vertrekpunten bieden voor de verbetering van het meststoftoedieningsbeleid onder de variabele neerslagcondities van droogtegevoelige gebieden. Het aan de bodem geven van gewasresten en dierlijke mest bleek zeer effectief voor het herstel van de negatieve K- en C-balansen.

Scenarioanalyse van grondbewerkings-, gewasrest- en bemestingseffecten op C-dynamiek

Gebaseerd op gegevens van 10 jaar veldproeven werd een scenarioanalyse uitgevoerd met het Century-rekenmodel, om de effecten te voorspellen van de veldactiviteiten op de dynamiek van C in de bodem. De volgende adviezen worden aangereikt:

1) in het kader van CT-systemen moet gemiddeld jaarlijks 50% (gelijkwaardig aan 1.3 t C) aan gewasresten worden teruggegeven aan de grond, om een acceptabel C–gehalte in de bodem te kunnen handhaven.
2) verhoging van het N-gehalte verlaagde de omzetsnelheid van organische stof in de bodem, maar dit was niet voldoende om meer C vast te leggen zonder aanvulling met organisch materiaal.

Synthese

Aan Duurzame Landbouw (conservation farming) wordt in China in toenemende mate aandacht geschonken. Het is de aangewezen manier om de milieuproblemen aan te pakken die worden veroorzaakt door (fysische) bodemdegradatie als gevolg van erosie. Er zijn sterke argumenten om traditionele landbouwmethoden op lokale schaal te combineren met moderne inzichten en up-to-date te maken. Een plaatsspecifieke combinatie van toediening van organische mest met gereduceerde grondbewerkingstechnieken zou gunstig zijn uit oogpunt van verhoging van de bodemvruchtbaarheid en besparing van energie en kunstmest. Onze studies geven aan dat verliezen aan bodemmateriaal door winderosie kunnen worden verminderd met 79%, wanneer boeren omschakelen van traditionele naar no-till bewerkingssystemen. Gemiddeld moet minstens 50% van de gewasresten aan de grond worden teruggegeven, om een acceptabel C- niveau te handhaven, afhankelijk van de totale gewasopbrengst (aan biomassa). Mest en maïsresten leverden effectieve organische stof en essentiële nutriënten, en hadden daardoor positieve effecten op de C-, N-, P-, en K- balansen. Bovenbedoelde “dragers” van organische stof droegen tevens bij aan de verbetering van de efficiëntie van het waterverbruik

Onderhavige studie heeft het inzicht vergroot in de complexe interacties, die optreden bij het management van de bodem(structuur) in wisselwerking met de toediening van gewasresten en de meststoffen in China's droogtegevoelige landbouwsystemen. Ook is aangetoond, dat de gestelde onderzoeksvragen alleen kunnen worden beantwoord door uit te gaan van een geïntegreerde benadering. Zo'n aanpak zou niet alleen moeten worden toegepast op veldproeven, waar landbouwkundige, technische en bodem-gerelateerde parameters moeten worden beoordeeld. Die integratie zou ook gestalte moeten krijgen in het combineren van veeljarig veldonderzoek met modellering en simulatie enerzijds en het verzamelen van klimatologische gegeven anderzijds.

摘要

前言

中国北方旱地面积广大，占中国国土陆地总面积的 50%以上，覆盖了 17 个省（自治区、直辖市）。该区人口占全国人口总数的 22%（不包括半湿润区）。旱地农作物以玉米和小麦为主，生产占全国产量 28%的粮食。旱地农业在中国的粮食生产中占有重要地位，然而，该区在中国仍处于最贫困地区。

中国北方旱农地区作物生产受到气候（干旱缺水且降水变异大）、地形（多山地坡地）、侵蚀、地力低薄如土壤有机质（SOM）和养分含量较低等因素制约。作物产量通常低而不稳，以至威胁作物生长，尤其该区土壤管理粗放如土地过度耕翻或过度放牧，而且每年作物秸秆大量带出农田土壤等，因而会对作物产量有很大影响。这些问题随着土地退化不断加重。

中国的土地退化面积目前已达 2.6 Mkm^2，占中国国土陆地面积的 27%，或占中国旱地总面积的 79%（旱地总面积为 3.3 Mkm^2，未包括极度干旱区）。在这些地区，由于肥沃表土层养分和有机质损失严重，农业土壤生产力受到极大威胁。因此，旱地土壤保持与土壤肥力恢复已经引起人们的高度重视。

自 1980 年代起，土壤保持耕作研究通过一些国内的和国际合作研究项目在中国展开。特别是 2002 年以来，随着沙尘暴、风蚀、水蚀、以及土地退化对环境的威胁不断增加，中国政府对土壤保持耕作的示范与推广采取了积极行动。中国土壤保持耕作面积目前仅占全球保持耕作面积的 0.2%，仅占全国耕地面积的 0.1%。其现状与中国耕地资源与土壤质量继续退化及其对土壤保持耕作需求的增加有着相当的距离。因此，加强土壤保持耕作及水分、养分、有机碳和节能技术研究在中国具有十分重要的意义。

问题的提出和研究目标

中国对土壤保持耕作措施的接受和采用一直较为缓慢，除了认识上、科学和技术等方面原因，还与多样的地区条件有关。目前，对旱农区特定区域保持耕作适宜性及有效实施因素等机理的研究尚还不足，对保持耕作可能引起的副效应还缺乏深入研

究。因此，有必要开展以下研究：(1) 研究保持耕作与气候变异性相互作用对作物产量与环境的影响；(2) 研究长期耕作措施对养分循环、土壤肥力与作物产量的影响。

该博士论文研究项目的总体目标旨在增强对中国北方旱区农作系统土壤保持耕作与养分管理及其相互影响的认识和理解。具体目标如下：

1. 对土壤保持耕作的需求及其前景进行综述评价；
2. 研究评价不同耕作措施和养分管理下，降水对作物产量与水分利用的影响；
3. 研究评价少耕条件下，作物残茬、牛粪和化肥配施对作物产量、养分与水分利用效率、养分平衡和土壤肥力指标的影响；
4. 研究评价耕作、残茬与施肥管理对土壤有机碳动态变化的影响。

该项目研究包括文献综述研究、长期田间试验研究以及动态模拟研究。文献综述分析以土壤保持耕作（中国和全球范围）和中国北方沙尘暴侵蚀研究为重点。 田间试验主要涉及到不同耕作、残茬和养分管理措施的影响。情景分析采用 Century 模型模拟预测土壤管理措施对土壤有机碳动态变化及土壤固碳潜力的影响。田间试验研究设在中国北方半湿润偏旱区的 4 个试验点，包括山西屯留、临汾和寿阳，河南洛阳。试验点位于 111°N 和 113°N，34°E 和 38°E 之间。

主要研究结果摘要

土壤保持耕作的潜在影响

通过对全球范围长期土壤保持耕作研究进展的综述研究，探讨分析了土壤保持耕作的潜在影响，如长期实施土壤保持耕作对碳固定、作物产量、水分与养分利用效率均有潜在的促进和改善作用。研究建议采用综合、易用且先进的技术对确保土壤保持耕作措施在中国北方旱区农作系统成功推广应用十分必要。尤其需要加强特定区域保持耕作的长期效应研究，发展建立经济适用的保持耕作技术体系。

土壤保持耕作的进展

通过对中国北方旱区保持耕作研究的综述研究，明确了实施少耕措施对作物产量和水分利用效率有促进作用，其增幅可达 35%。作物残茬地表覆盖应视地区气候条件而定；年均气温低于 7°C 的地区应以秸秆还田为宜。根据旱农区域特点不同，特定区

域保持耕作的选择（包括与耕作相关的管理措施如残茬、肥料、作物轮作、水分及农药管理等）侧重点亦有不同：1) 强风蚀和沙漠化严重的西北干旱区：以免耕休闲，保持高留茬覆盖和增加有机与无机肥配施为重点；2) 强水蚀的黄土高原区：以种植覆盖作物，保持高留茬覆盖与等高/条带种植相结合为重点；3) 东北冷凉区：以少耕/垄作并保持高留茬覆盖为重点；和 4) 华北平原区：以保持作物残茬，免耕播种和平衡施肥为重点。

沙尘暴侵蚀对土壤碳和氮损失的影响

文献综述研究重点讨论分析了中国北方沙尘暴有关的土壤侵蚀与养分损失的因果关系。研究表明中国北方沙尘暴导致的土壤养分损失是相当可观的，与土壤过度耕种及传统耕作措施影响有关。每年由中国北方沙尘暴导致的土壤C和N损失范围，若以每cm表土估算，分别在 53-1044 kg ha^{-1}和 5-90 kg ha^{-1}。田间试验研究结果得知，当农民改变传统土壤耕作方式为保持措施如免耕，风蚀导致的土壤损失量可降低 79%。

降水变异对雨养作物产量的影响

中国北方旱农地区作物生产受到干旱缺水和降水变异的极大限制。这一章节重点对月-季节-年降水量变异与雨养小麦和玉米产量间关系进行分析研究。数据分析主要基于中国北方半湿润偏旱区旱农研究项目在多点如山西屯留、临汾和寿阳，河南洛阳等地和多年的田间试验研究。旱地小麦和玉米产量在很大程度取决于降水分布。对小麦而言，分析研究发现小麦籽粒产量(GY)和年降水量(AR)、以及小麦 GY 和播前土壤水分(SWS)都存在线性相关。寿阳玉米 GY 对 6、7 和 4 月降水量较为敏感。结果表明，减轻作物水分胁迫相应措施的制定与实施必须依降水类型而确定。该结果尤其适用于以土壤和水分保持为目标的耕作与农作制度及其相关措施的有效实施。

耕作和作物残茬对雨养小麦和玉米生产的影响

在中国北方半湿润偏旱区的山西和河南等 4 个试验点实施开展了小麦和玉米的耕作与作物残茬管理的田间试验。研究评价了不同耕作与残茬应用方式对土壤物理条件、土壤贮水、水分利用、作物产量与水分利用效率的影响。土壤保持耕作与残茬应用

措施相结合显示出各种效益。如土壤容重的变化改善了水分保持并加强了土壤保护以免遭风蚀。实施保持耕作增加了夏休闲和雨季水分贮存并减少水分损失，因而改善了作物水分有效性。保持耕作措施通常具有增产效果。如少耕的春玉米和冬小麦产量分别提高 22%和 7%。免耕作物产量与传统耕作相近。

长期作物残茬、粪肥与化肥配施对旱作玉米的影响

长期田间试验研究自 1993 年起在中国北方半湿润偏旱的山西寿阳旱农试区实施，目前仍在继续。研究评价了春玉米种植体系在少耕条件下，作物残茬、牛粪与 NP 化肥配施对玉米产量、养分利用效率、养分平衡与土壤肥力的影响。

田间试验结果表明，作物产量随时间呈下降趋势，与生育期总降水量变化及季节降水分布有关，还与土壤钾(K)的耗竭有关。作物残茬、牛粪与 NP 化肥平衡配施的玉米产量、氮的利用率(NRE)与水分利用效率(WUE)均为最高。秋季采取秸秆还田并增施粪肥的少耕措施不仅节省劳力且能降低风蚀。研究建议 N 肥针对性分施，如针对当季作物需求(回应农业 response farming) 分期施肥可能会进一步提高 N 的利用率，然而，N 肥针对性分施潜力还有待探讨。

经过多元回归模型分析得知，局部 N、P 和 K 平衡与播前土壤水分(SWS)及作物生育期降水量(GSR)年变异有很大相关。从养分平衡和土壤肥力指标分析看出，多数处理的养分投入量距平衡还较远。研究总结得出：“ 理想的土壤肥力水平” 和“ 回应养分管理” 概念适用于改善旱农地区降水多变异条件下的养分管理。作物残茬回田和增施粪肥是恢复 K 和 C 平衡的最有效途径。

耕作、残茬与施肥管理对土壤有机碳动态变化影响的情景分析

情景分析主要基于 10 年田间试验，采用 Century 模型模拟预测了不同土壤管理措施对土壤有机碳(SOC)动态变化的影响。主要研究结果如下：1) 采用保持耕作措施和残茬回田是维持和提高土壤有机碳的有效途径。维持土壤有机碳平衡的年均残茬投入量至少在 50%(相当 1.3 t C)。2) 增加无机 N 肥可减缓 SOC 的分解速率。然而，单施无机 N 而不投入有机 C (作物残茬或粪肥)，对土壤 C 库的净增贡献不大。

总结

针对中国近年来因过量施肥和侵蚀导致的土壤退化等引发的环境问题不断增加，采用保持农作措施在中国引起人们的极大关注。特别是注重将中国地方特色的传统保持农作措施与现代农业技术融合。如因地制宜采用有机肥与少耕结合的措施对于培肥地力、节能省肥具有积极影响，并且还能保护土壤免遭由所谓“现代”机械化农业体系导致的侵蚀。

研究表明当农民改变传统土壤耕作方式为保持措施如免耕，风蚀导致的土壤损失量可降低 79%。有机与无机肥平衡配施可使土壤有机碳随时间缓慢增加。维持土壤有机碳平衡的年均作物残茬回田量至少在 50%(相当 1.3 t C)，还要根据作物产量而确定。粪肥和秸秆还田可提供土壤有效碳和必要养分，因此，有助增进 C 平衡及 N、P 和 K 平衡。有机残茬还田有利于增加水分利用效率。

该项目研究增强了我们对中国北方旱区农作系统土壤、作物残茬与养分管理之间复杂性互作关系的认识和理解。同时说明只有运用综合研究方法才能对这些复杂问题给予科学的解答。这种综合的方法不仅要通过田间试验，获取农艺的、技术的和土壤有关的参数，还应该将（长期）田间试验与模型模拟研究以及气象资料收集和分析相结合。

Curriculum vitae

Xiaobin Wang was born on November 17, 1955 in Beijing, China.

She got BSc in Soil Agro-Chemistry at Northwestern Agricultural University in Shaanxi, China in 1981. She was awarded a MSc. in Soil Management at the Graduate School of CAAS in Beijing in 1988 (her thesis entitled "Crop growth responses to soil water and fertilizer in dry farmland" was selected for ‘A collection of Master Theses of Excellence’ (1987-1988) at the Graduate School of CAAS).

She has been employed by the Soil and Fertilizer Institute (now called Institute of Agricultural Resources and Regional Planning), Chinese Academy of Agricultural Sciences (CAAS) since 1982. At CAAS, she has been involved in the national dryland farming projects coordinated by CAAS for almost 25 years, with the following projects: .

- Tillage effects on soil physical condition, water and crop production in dryland farming areas (1982-1985).
- Alternative tillage techniques for soil water conservation in rainfed farming areas (1986-1990);
- Conservation tillage systems in main dryland farming regions, and Dryland nutrient balance and residue management (1991-1995);
- Dryland nutrient cycling and N use efficiency (1996-2000);
- Tillage technology systems for water/nutrient balance and effective use (2001-2005); and
- Simulation of carbon cycle dynamics under conservation tillage system in dryland (2005-2007).

She has received various awards and scholarships, including the National Natural Science Foundation of China Research Award (2005), a Scholarship awarded by World University Service of Canada for the Soil Conservation Program (1993-1994), and a Scholarship awarded by China Scholarship Council (2002-2003).

Contacts with Wageningen University were initiated around 1990, and plans for pursuing a PhD study at Wageningen University were made in 1999. In 2003, she got a scholarship from Wageningen University. This thesis is a result of that scholarship.

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