Soil Hydraulic Properties and Water Balance under Various Soil Management Regimes on the Loess Plateau, China

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Abstract

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Water is the most limited factor for crop production in dryland farming. In the work underlying this thesis soil hydraulic properties and water balance under various soil management regimes in the Chinese Loess Plateau were evaluated in laboratory studies, field experiments and simulations. Several methods for measuring soil hydraulic properties were also tested. The study was carried out at three sites on the Loess Plateau: Mizhi in the northern part, Heyang in the southeast and Yangling at the southern edge of the plateau.

The saturated hydraulic conductivity of the loess soil at these sites was similar. However, the unsaturated hydraulic conductivity, $K(\theta)$, of the soil was higher at the northern site (Mizhi) than at the southern sites (Heyang and Yangling), and soil water retention showed the opposite pattern. Laboratory studies demonstrated that soil compaction significantly influenced soil hydraulic properties, reducing the saturated hydraulic conductivity and altering the shape of the soil water retention curves at two of the sites (Mizhi and Heyang). At the Yangling site long-term application of organic manure increased water retention in the low tension range and decreased the unsaturated hydraulic conductivity, $K(\theta)$, at relatively high water contents in the surface layer (0-5 cm). However, it did not affect the saturated hydraulic conductivity. These, and other, effects of soil management practices on the soils' hydraulic properties alter the partitioning of the water balance. To assess these effects in a winter wheat system, an integrated ecosystem model was calibrated using the results of a three-year field experiment, and a long-term (45-year) simulation was run to evaluate the sustainability of wheat production under various soil management regimes. The simulations showed that mulching optimized the partitioning of the water balance components, decreasing soil evaporation and increasing both transpiration and deep percolation, leading to increased wheat yields and WUE. Furthermore, mulching significantly improved the quantity and frequency of deep percolation, which should enhance the groundwater recharge potential. Incorporating mulching into the winter wheat-summer fallow system could be a sustainable management strategy for the Loess Plateau. Increasing the organic matter content of the soil could be another beneficial approach, if sufficient resources were available. Soil compaction caused the most unfavourable partitioning of water balance, leading to the lowest yield and WUE of all the treatments. Considering all of the factors involved, the duration of bare fallow should not be less than 30 days to maximise the benefits of producing green manure or fodder without significantly reducing the wheat yield and WUE.

Keywords: Winter wheat; Mulch; Fallow crop; Soil compaction; Water balance; Water use efficiency; Modelling

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Appendix

Papers I-V

This thesis is based on the following papers, which are referred to by the corresponding Roman numerals:

I. Zhang, S., Lövdahl, L. and Grip, H. Soil hydraulic properties of two loess soils in China measured by various field-scale and laboratory methods. *Submitted.*

II. Zhang, S., Grip, H. and Lövdahl, L. 2005. Effect of soil compaction on hydraulic properties of two loess soils in China. *Soil & Tillage Research, in press.*

III. Zhang, S., Yang, X., Wiss, M., Grip, H. and Lövdahl, L. Changes in physical properties of a loess soil in China following two long-term fertilization regimes. *Submitted.*

IV. Zhang, S., Lövdahl, L., Grip, H. and Jansson, P.-E. Modelling the effects of mulching and fallow cropping on water balance in the Chinese Loess Plateau. *Submitted.*

V. Zhang, S., Simelton, E., Lövdahl, L., Grip, H. and Chen, D. Simulated long-term effects of different soil management regimes on the water balance in the Loess Plateau, China. *Submitted.*

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Introduction

Large areas of the world are dry, and many are too dry for any agriculture. However, 'dryland agriculture' is practiced on around 40% of the world's land, most of it (60%) in developing countries (UNEP, 1997). Due to the world's growing population, agriculturalists are facing great challenges, especially since the arable land area is decreasing. Moreover, limited fresh water resources and insufficient ground water recharge make it impossible to further enlarge the irrigated area. Hence, agricultural scientists have paid considerable attention to dryland agriculture. The most common characteristics of dryland farming are that precipitation is considerably lower than optimal and unevenly distributed during the crop growing period, resulting in low, variable yields and (thus) inefficient water use. In the past decades scientists have made strenuous efforts and great advances in improving water use efficiency by techniques such as harvesting water (Kolarkar et al., 1983), runoff agriculture (Luebs, 1983) and terracing land (Zingg and Hauser, 1959). Water use can also be improved by appropriate management strategies, for example fallow practice (Li and Xiao, 1992), conservation tillage (Tanaka and Anderson, 1997), no tillage or mulching (Unger, 1978; Fabrizzi et al., 2005), crop rotation (Li et al., 2000; Huang et al., 2003b), proper fertilization (Zaongo et al., 1997; Fan et al., 2005), and also breeding (Tripathi et al., 2000). However, the development of dryland farming in the world is not geographically balanced. In developed countries high productivity of drylands has been maintained, whereas its productivity tends to be very low in developing countries (Li, 2004). Therefore, continued efforts are needed in dryland agriculture research in order to feed the rapidly growing population.

In China, dryland farming is practised on about a third of the arable land, a large part of which (about 40 %) is situated on the famous Chinese Loess Plateau (Li, 2004). The Loess Plateau covers an area of 623,800 km^2 with population of about 90 million. Its climate is mostly semiarid, with annual precipitation ranging from 150-300 mm in the north to 500-700 mm in the south (Li and Xiao, 1992). Most of the annual precipitation (50 – 60%) falls as rain during the summer, from June to September. Groundwater resources are sparse and deep, so most of the farmland on the Loess Plateau is dryland and must, therefore, rely solely on rainfall (Li and Xiao, 1992). Sustaining the agricultural production in the Loess Plateau is very important to ensure that sufficient food is produced for the growing population. It has been suggested that by optimizing the management of soil water and nutrients, agricultural production in the Loess Plateau could be increased substantially, perhaps as much as threefold (Fan and Zhang, 2000). Winter wheat, the main crop on a large part of the Loess Plateau, is conventionally cultivated as a single crop per year followed by about three months summer fallow. The fallow period coincides with the rainy season and it is believed that water is stored in the soil during this period for the following wheat crop. During the past 20 years, wheat yield has been increased by fertilizer applications, but this practice has resulted in increasing soil-water depletion (Huang et al., 2003a). Consequently, soil water is not fully replenished during the fallow, and where a dry subsoil layer has formed (Huang et al., 2002) crop yield strongly varies with rainfall within the growing season (Li, 2001). Hence, the greatest threat to winter wheat production is water shortage.

Finding ways to improve water use efficiency (WUE) and to maintain sustainable productivity are crucial tasks for dryland farming research. Breeding plants with water-conserving traits is clearly an important component of such research. However, developing appropriate soil management practices is also important, since the soil management regime affects water use efficiency through its effects on the amounts of water lost via evaporation and water storage in the root zone and deeper layers of the soil. Mulching is regarded as one of the best ways to improve water retention in the soil and to reduce soil evaporation (Steiner, 1989; Li and Xiao, 1992; Baumhardt and Jones, 2002). Application of organic materials also improves soil properties, and thus increases WUE (Unger and Stewart, 1974; Schjonning et al., 1994; Obi and Ebo, 1995; Arriaga and Lowery, 2003; Edmeades, 2003). However, soil compaction caused by field operations adversely affects soil properties, resulting in decreased WUE (Lipiec and Hatano, 2003; Sillon et al., 2003).

Maximising the sustainability of the agriculture in areas such as the Loess Plateau requires the development and implementation of appropriate management practices that can optimize the long-term partitioning of the water balance components and provide relatively stable performance under varying climate conditions. Evaluating the sustainability of crop productivity under diverse management regimes in the field needs many long-term experiments, which are costly and time consuming. Alternatively, it can be evaluated much more cheaply and quickly using simulations. Hence, simulations can play an important role in elucidating the interactions between soil management regimes and crop responses in highly variable climates. Models can be used for comparing different scenarios and simulating long-term interactions between soil type, management and climate that cannot be studied experimentally (Asseng et al., 2001; Eckersten et al., 2001; Keating et al., 2002; Eitzinger et al., 2003). Few studies have investigated the effects of various management practices on soil hydraulic properties on the Loess Plateau, and the resulting effects on water balance partitioning and the sustainability of crop production (Huang and Zhong, 2003). Furthermore, none of the studies have considered the effects of soil management regimes on deep percolation, which may contribute to groundwater recharge. The groundwater level has been decreasing in the Loess Plateau in recent decades (Li and Ma, 2004), which in turn leads to decreased discharge into streams and rivers. Therefore, much more research is needed to increase production stability and groundwater recharge.

Objectives

The overall objectives of the work underlying this thesis were to evaluate the effects of different soil management regimes on soil hydraulic properties, and (thus) on water balance and crop (e.g. winter wheat) production in the Loess

Plateau of China, then to suggest a sound management strategy based on soil physical properties. The specific objectives were as follows:

To determine hydraulic properties of the loess soils by field and laboratory methods (Paper I).

To determine the effects of soil compaction on soil hydraulic properties (Paper II)

To evaluate the effects of long-term applications of manure and fertilizer on soil hydraulic properties (Paper III)

To calibrate a model and combine field data to evaluate the effects of mulching and fallow crops on the water balance and winter wheat production (Paper IV).

To evaluate the long-term effects of various soil management regimes on water balance and winter wheat production (Paper V).

Literature review

Methods to determine hydraulic properties

Knowledge of soil hydraulic properties is important for describing and predicting movements of water and solutes through soils, which may be related to many agronomic, engineering, and environmental fields of research. Key soil hydraulic properties include the saturated hydraulic conductivity (K_s), the unsaturated hydraulic conductivity function – $K(\psi)$, $K(\theta)$ or $K(\vartheta)$, where ψ is water potential, θ is volumetric water content and ϑ is water volume ratio – and the soil moisture retention curve or soil water characteristic curve. In recent decades many direct methods have been developed for measuring hydraulic properties in the field, for example the internal drainage method (Hillel et al., 1972; Libardi et al., 1980), the zero plane flux method (Richards et al., 1956) and the Guelph permeameter method (Reynolds and Elrick, 1985), and in the laboratory, e.g. the hot-air method (Arya et al., 1975), the out-flow method (Gardner, 1956) and the constant head method (Klute and Dirksen, 1986). Interestingly, comparative studies of the different methods have shown that their relative accuracy varies depending on the soil type and field conditions, as shown by the following examples. The hot-air has been shown to overestimate hydraulic conductivity of Andosols compared with the field internal drainage or zero plane flux methods (Fontes et al., 2004). The water retention values at low tensions measured with undisturbed cores are greater than those observed in the field (Fontes et al., 2004). The hot-air method is thought to be suitable for loamy to silty soils (van Grinsven et al., 1985; Gieske and De Vries, 1990), but fails in coarse-textured soils (Stolte et al., 1994). On sandy loam and silt loam soils water retention curves generated using data obtained by the undisturbed soil core and field internal drainage methods agree well, but give saturated conductivity values that are up to three times higher than those obtained using the Guelph permeameter (Paige and Hillel, 1993). In addition, both the soil water retention curves and hydraulic conductivity values obtained on a sandy loam soil using various measuring techniques differed considerably (Mallants et al., 1997). Hence, no single method has been developed that performs very well in a wide range of circumstances and for all soil types. Most direct methods require restrictive initial and boundary conditions, which make measurements time consuming, range restrictive and expensive. Other investigators, therefore, have sought to derive soil hydraulic properties from moisture retention curves of undisturbed soil cores measured in the laboratory (Brooks and Corey, 1964; Mualem, 1976; van Genuchten, 1980; Kosugi, 1999). Various indirect methods have also been used – including predicting hydraulic properties from more easily measured soil properties, such as texture, bulk density or organic matter content, i.e. by using pedo-transfer functions (PTFs) and inverse modeling techniques. Wösten et al. have provided a good review of pedo-transfer functions (Wösten, 2001). Since PTFs predict missing characteristics from already available basic soil data, they have the clear advantages of being relatively inexpensive, easy to derive and convenient to use. However, for application at a specific point, prediction by a PTF might be inadequate. In such cases, direct measurement is the only option. PTFs should not be used to make predictions for soils that are outside the range of soils used to derive them. In other words, use of PTFs for interpolation purposes is valid, but they are not recommended for extrapolation.

Inverse estimation of soil hydraulic properties has proven to be a reliable method for determining soil hydraulic parameters in either the laboratory or the field, and a thorough review has been provided (Hopmans and Simunek, 1999). However, the inverse modeling is associated with problems of parameter identifiability, uniqueness and stability (Durner et al., 1999). In addition, the choice of method is often limited by the available in situ or laboratory facilities. In situ methods, such as the internal drainage method (Hillel et al., 1972), Guelph permeameter method (Reynolds and Elrick, 1983), and laboratory methods such as the undisturbed soil core method (Klute and Dirksen, 1986) and the hot-air method (Arya et al., 1975), are among the most widely used. In the Loess Plateau very little information is available on hydraulic properties (Stolte et al., 2003) in the literature. Furthermore, given the variability of results obtained when different methods are applied to different soils, it might be necessary to use more than one method to determine soil hydraulic properties in the area of interest, to ensure that the flow dynamics in the soil are well understood and that the data obtained are reliable inputs for simulations.

Effects of soil management on hydraulic properties

Soil compaction

One feature of modern agriculture, even in developing countries is that the use of machinery, which causes soil compaction, is becoming more and more frequent in field operations. Soil compaction is a global problem, affecting about 68 Mha of land (Oldeman et al., 1991). The detrimental effects of soil compaction caused by traffic include increased bulk density, decreased porosity, and adverse shifts in pore shapes and size distributions (Flowers and Lal, 1998; Radford et al., 2000; Richard et al., 2001; Pagliai et al., 2003). Changes in these basic properties alter the soil's water retention and hydraulic conductivity characteristics, which in turn affect the infiltration ability of the soil and its plant-available water storage capacity. A change in pore size distribution may also negatively affect root growth (Tippkotter, 1983). Consequently, soil compaction can have serious effects on soil quality parameters and, hence, on crop growth and environmental quality. The effects of soil compaction depend on the compaction effort, soil types, water status and cropping system involved (Hill and Sumner, 1967; Kirkegaard et al., 1993; Etana, 1995; Radford et al., 2000; Miller et al., 2002a; Green et al., 2003; Sillon et al., 2003; Tarawally et al., 2004). It has also been shown that soil to which organic manure has been applied or has not been tilled is more resistant to compaction than other soil (Etana, 1995; Tebrugge and During, 1999). Radford et al. (2000) studied responses of soil properties in a clay soil (Vertisol) to harvester traffic under three axle loads (0, 10 and 12 Mg) in wet soil conditions. The compaction applied caused a statistically significant increase in the soil's bulk density, and decreased its unsaturated hydraulic conductivity. Hill and Sumner (1967) measured soil water retention for a variety of soils artificially compacted to various bulk densities. Compaction-induced changes in the measured water retention curves varied depending on the soil textural class. Sillon et al. (2003) found that a calcareous soil had a higher hydraulic conductivity, across the whole range of water ratios tested, following a compaction treatment. However, the hydraulic conductivity of a loess soil was similar following all treatments with water ratios >0.3, and in drier conditions (i.e. water ratios <0.3), the hydraulic conductivity was lowest in a spring-tilled plot they examined and highest following the compaction treatment. Miller et al. (2002a) reported soil water characteristic curves (SWCCs) to be more sensitive to changes in compaction effort than changes in water content when compaction occurred. In addition, SWCCs for soils compacted in the laboratory and the field showed similar changes in hydraulic properties. However, Green et al. (2003) noted that field traffic had significant effects on soil compaction and related hydraulic properties in some soils and climates, while in others, field and temporal variations were so great that no effects of wheel tracks were significant. Most studies have found that subsoil compaction caused by high axle loads persist for a long time and that it is independent of the prior soil water content (Etana, 1995; Chamen et al., 2003). In addition, experimental data relating the effect of soil compaction to unsaturated flows are very limited (Lipiec and Hatano, 2003). Thus, further studies are needed to accumulate a database for model applications and to extend our knowledge in this respect.

Organic matter application

Various types of organic materials have been found to have similar effects on soil physical properties (Barzegar et al., 2002), and almost all studies indicate that application of organic materials improves soil properties (Khaleel et al., 1981; Celik et al., 2004; Mando et al., 2005). However, reported effects of manure additions on soils' hydraulic properties, such as water retention and saturated hydraulic conductivity, are inconsistent. Unger and Stewart (1974) reported that water contents at low tensions (< 150 kPa) were significantly higher for manure-treated soils than for untreated soils, but they found no significant difference at 1500 kPa tension. Sommerfeldt and Chang (1987) and Miller et al. found that manure amendment significantly ($P \leq 0.05$) increased soil water retention (at 0-5 and 10-15 cm depths) compared with the control across the whole tension range between 0 and 1500 kPa (Miller et al., 2002b). Obi and Ebo (1995) found that poultry manure significantly increased water retention at tensions between 0 and

33 kPa, but decreased it at tensions between 33 and 1500 kPa. In contrast, Schjonning et al. (1994) reported that soil water retention (tension range: 0.6 to 1500 kPa) was not significantly affected by inputs of either organic or inorganic fertilizer compared with unfertilized controls. Thus, changes in soil water retention may depend more on the soil type and initial carbon content than the addition of organic materials *per se*. Since soil porosity increases following additions of organic manure, they are also expected to increase the saturated hydraulic conductivity (K_s). However, available data indicate that large variations in K_s tend to follow organic manure applications. A number of authors have found that saturated hydraulic conductivity in tested soils have significantly increased following applications of diverse kinds of organic matter, including poultry manure (Mbagwu, 1992; Obi and Ebo, 1995), cattle manure (Schjonning et al., 2002) and compost (Gonzalez and Cooperband, 2002). Conversely, others have found the saturated hydraulic conductivity to be unaffected by applied manure (Well and Kroontje, 1979; Sommerfeldt and Chang, 1987; Shirani et al., 2002; Arriaga and Lowery, 2003). However, Miller et al. (2002b) detected differences in the saturated conductivity responses between manure and control treatments during observations over two years. In one year the K_s value of manure-treated soil was significantly higher than the control in a dryland zone, but not in an irrigated zone, while in the other year the opposite trends were found. Hence, no universal pattern appears to apply to all conditions in real situations.

There is very little information in the literature about the effects of manure applications on unsaturated hydraulic conductivity, although Miller et al. (2002b) presented field measurements obtained using a tension infiltrometer showing that manure treatment had little or no significant effect on $K(\Psi)$ values. Therefore, there is a need for further investigation on the influence of manure applications on unsaturated flow. Normally unsaturated conditions prevail in the field and consequently this is of importance for both dryland and irrigated land management.

Surface mulching

Surface mulching or no tillage can increase infiltration rates by increasing the abundance of biopores or macropore connectivity (Tebrugge and During, 1999; Green et al., 2003). The soil water retention curve is changed at the wet end of the scale because the abundance of large pores increases in the absence of tillage (Hamblin and Tennant, 1981; Mapa et al., 1986). Furthermore, organic surface mulching will also increase soil organic matter contents (Tebrugge and During, 1999), and in some respects surface mulching has similar effects to the addition of organic manure on soil properties. Nevertheless, the changes in total porosity and bulk density induced by these treatments differ (Haynes and Naidu, 1998; Tebrugge and During, 1999).

Effects of soil management on water balance and crop production

The magnitude of each of the water balance components can be significantly affected by the soil management regime. For instance, soil compaction can adversely affect the soil water balance by decreasing deep percolation to the groundwater and simultaneously increasing surface runoff (Lipiec et al., 2003; Stenitzer and Murer, 2003b). A field study by Sillon etal. (2003) showed that the effects of compaction on soil evaporation varied from soil to soil; increasing it on a calcareous soil but not on a loess soil. These adverse effects of compaction reduce water availability for crop use and nutrient transport to roots, which subsequently reduce crop yield and water use efficiency (Flowers and Lal, 1998; Lipiec and Hatano, 2003; Motavalli et al., 2003; Nevens and Reheul, 2003; Stenitzer and Murer, 2003a). Furthermore, the reductions in crop yield can persist for a long time, especially if subsoil compaction has occurred (Etana, 1995; Alakukku, 1996). However, a short-term field study by Radford et al. (2000) showed that wheat yield was not affected by soil compaction, although wheat seedlings were not fully established. In coarse-textured soils rainfed lowland rice may benefit from decreased deep percolation caused by subsoil compaction (Sharma et al., 1995).

Application of organic materials is particularly beneficial for water infiltration and drainage since it enhances soil porosity and the pore size distribution (Pagliai et al., 2004; Zougmore et al., 2004). In addition, application of organic manure reduced soil evaporation and the reduction was correlated with the amount of manure added in a laboratory column study described by Unger and Stewart (1974). Many studies have also reported that crop yield is increased under manure application (Shirani et al., 2002; Mando et al., 2005). A summary of 14 long-term experiments showed that crop yield was not significantly different between manure and chemical fertilizer treatments (Edmeades, 2003).

Surface mulching significantly reduces soil evaporation and increases water storage (Unger, 1978; Sinclair and Amir, 1996; Li et al., 1999; Li, 2003; Huang et al., 2005). However, mulch effects depend on the soil type, rainfall and evaporative demand (Wicks et al., 1994; Tolk et al., 1999; Ji and Unger, 2001; Lampurlanes et al., 2002). In a two-year field study reported by Fabrizzi et al. (2005) soils that were not tilled stored more water than soils that were minimally tilled during the critical growth stage in the corn growing season and most of the wheat-growing season, but corn and wheat yields were similar between tillage treatments. On the Loess Plateau of China, a previous one-year field study demonstrated that mulched soil had a higher water content during both the wheat growing season and the fallow period (Wang et al., 2001). Other investigations have found that mulching increases the yield of winter wheat (Zhang et al., 1999; Liang et al., 2002).

Generally, the water balance has been roughly calculated on the basis of mass balance, ignoring runoff or deep percolation because of the difficulties associated with measuring these variables (Yunusa et al., 1994; Sharma et al., 1998; Huang et al., 2005). Several studies in the Loess Plateau have been more concerned with the effects of soil management and cropping systems on crop yield and water use efficiency than on the complete water balance (Li et al., 2000; Lu et al., 2003; Fan et al., 2005; Huang et al., 2005). Therefore, quantitative analyses of the partitioning of water balance components under various soil management practices are needed. Due to climatic variability, it is difficult to evaluate the long-term effectiveness of a soil management system from short-term studies. Only long-term analyses are likely to give a clear indication of the risks associated with management effects on crop yield and water balance components (Keating et al., 2002), but empirical analyses of this kind are costly and do not generate the required results quickly enough to guide interventions in the near future. However, simulations can be powerful tools for extrapolating short-term experimental results and for analyzing the effects of possible management practices on production and water balance across the range of climatic variations found within a given location. In recent decades a number of models designed to simulate crop growth and water balance of soil-crop systems have been developed. and reviewed (Connolly, 1998; Lipiec et al., 2003). Models, such as EPIC (for example, Cabelguenne et al., 1999), APSIM (Asseng, et al., 2001), have been used to simulate interactions between climate, plant available soil water and crop management. SOIL/SOILN models have been applied to model water flow and wheat production under climate change in Sweden (Eckersten et al., 2001). On the Loess Plateau winter wheat yield and water use efficiency were simulated using the WAVES model based on crop transpiration and harvest index, but the detailed water balance was not evaluated (Kang et al., 2003). The ideal model to use depends on the purpose or proposed application of the model and the degree of detail required.

Materials and methods

Sites description and soil characteristics

The experiments were mainly conducted at two sites in the Shaanxi Province of China (Fig. 1), one in the county of Mizhi (N 37°46′, E 110°7′, altitude 1022 m) and one in Heyang county (N 35°19′37″, E 110°4′57″, altitude 910 m). A third site was used to evaluate the effects of organic matter on soil hydraulic properties in a long-term experiment in Yangling (34° 4′ N, 108° 2′ E, 534 m a.s.l.), also in the Shaanxi Province. The Mizhi site, located in the northern part of the Loess Plateau, is gullied and ridged, while the Heyang highland is located on a large level area in the south part of the Loess Plateau. Yangling is located in the flat Guanzhong area at the southern edge of the Loess Plateau. The groundwater table is at about 100 m, 60 m and 30 m, respectively, below the soil surface for most of the year at these sites. Mean annual precipitation in the past 20 years (1980-2000) was 400, 586 and 600 mm, respectively.

According to the USDA texture classification system, the soils are defined as silt loam and according to the FAO-Unesco soil map (FAO-Unesco, 1974) the soil types are Calcic Cambisols at the northern site and Chromic Cambisols at the southern sites.

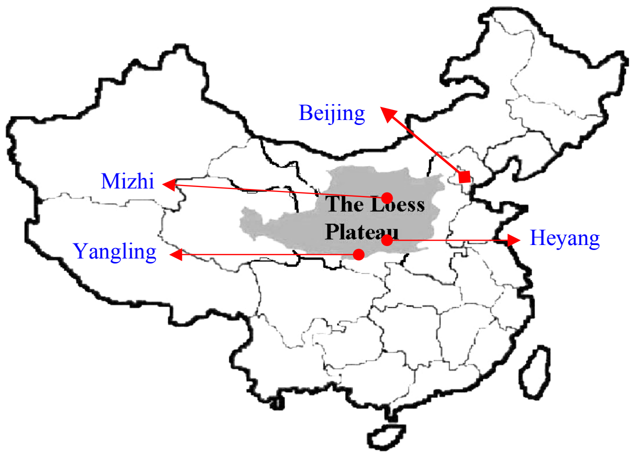

Fig. 1. Locations of the experimental sites.

Laboratory studies

Undisturbed soil cores were collected from ten different soil depths down to 205 cm at the Mizhi and Heyang sites and from two depths (0-5 and 10-15 cm) at the Yangling site for measuring soil water retention curves and saturated hydraulic conductivities using the standard tension plate and constant head methods (Klute and Dirksen, 1986), respectively. The unsaturated hydraulic conductivity was measured by the hot-air method (Arya et al., 1975) for the upper two soil layers (0-5 and 10-15 cm) from each site. Some of the soil cores from the upper two depths were used to measure those hydraulic parameters after that the soil had been compacted to three different compaction levels by volume; no compaction (C0), 10% (C1) and 20 % (C2). Soil cores from the Yangling site included soils with three different levels of organic matter. Detailed descriptions of the methods are presented in Papers I - III.

Based on the water retention curve from the undisturbed soil cores, the unsaturated hydraulic conductivity can be predicted by the models of van Genuchten (1980) (VG) or Brooks-Corey (1964) (BC).
The van Genuchten (1980) model for K

$$K(S_e) = K_s S_e^{\tau}[1-(1-S_e^{1/m})^m]^2 \qquad (1)$$

was derived by combining Mualem's model (Mualem, 1976) with Eq (2), where K is the hydraulic conductivity, S_e (the effective saturation) = $(\theta-\theta_r)/(\theta_s-\theta_r)$ (where s and r indicate the saturated and residual values of the volumetric moisture content, respectively), K_s is saturated hydraulic conductivity, τ is a pore interaction factor, assumed to be 0.5 by van Genuchten, and α and n are determined by least square fitting of

$$S_e = \frac{1}{\left[1+(\alpha\psi)^n\right]^m} \tag{2}$$

where α is a parameter, m = 1-1/n, and ψ is tension (kPa).

The Brooks-Corey (1964) model for K

$$K(S_e) = K_s S_e^{2.5+2/\lambda} \tag{3}$$

was obtained by coupling the Mualem (1976) model with the water retention curve in Eq. (4)

$$S_e = \left(\frac{\psi}{\psi_a}\right)^{-\lambda}, \quad \psi > \psi_a \tag{4a}$$

$$S_e = 1.0, \qquad \psi \leq \psi_a \tag{4b}$$

where ψ_a is the air-entry tension, and λ is a pore size distribution index.

Field study

The soil hydraulic properties were also determined in the field by the internal drainage and Guelph permeameter methods at the Heyang site at different depths (see Paper I).

To assess the effects of various soil management practices on winter wheat production and water balance, a three-year field experiment was conducted in Heyang (Paper IV). The field crop was a local variety of winter wheat (Dongfeng number one). The experiment included three treatments; 1. Conventional management, where wheat was sown in October and harvested in June after which the soil was ploughed and left bare until next sowing time; 2. Mulching, similar to the conventional management, but air-dried wheat straw (0.8 kg m^{-2}) was applied on the soil surface at the start of the experiment and then kept at the soil surface during the whole experiment period. After each harvest some wheat straw was added to compensate the loss from decomposition and before sowing the mulch material was temporarily removed when the fertilizers were mixed into the soil; 3. Conventional management with fallow crop, similar to the conventional management, but during the fallow period a fallow crop (Bean) was grown and harvested about one month before wheat sowing. The harvested bean biomass was immediately incorporated into the soil by ploughing.

Field measurements included determinations of soil moisture profiles, plant measurements (height, leaf area and yields) and climatic variables (air temperature, relative humidity, precipitation, wind speed and global radiation) (Paper IV). Soil moisture contents were measured at four depths (10, 40, 100 and

200 cm) by TDR (Time Domain Reflectometry) sensors. The TDR sensors were calibrated by comparing the gravimetric soil water contents and TDR readings throughout the experimental period in each field plot, except when the soil was partially or fully frozen.

Modelling

In the simulations a one dimensional physically based soil-crop model, the CoupModel (Jansson and Moon, 2001; Jansson and Karlberg, 2004) was used. This model is designed to simulate water, energy, carbon and nitrogen processes in an ecosystem, and couples the former SOIL (Jansson and Halldin, 1979; Johnsson and Jansson, 1991; McGechan et al., 1997; Jansson et al., 1999) and SOIL-N (Johnsson et al., 1987; Katterer et al., 1997; Eckersten et al., 2001) models. In the model the soil water balance depends on the ability of water from rainfall or irrigation to enter the soil through the soil surface and to be stored in the soil. Soil evaporation is calculated using a surface energy balance approach. Water uptake is assumed to be equal to plant transpiration, and is a function of potential transpiration, soil moisture and root distribution. Potential transpiration is calculated using the Penman-Monteith equation. Deep percolation is judged to occur when water is transmitted beyond the bottom layer of the soil profile (in the present study, 2.4 m). Snow dynamics and frozen conditions are also described in the model. The plant growth is calculated as the potential yield, i.e. the yield is not limited by pests and diseases, but only by the abiotic factors temperature, solar radiation, water and nitrogen supply.

Table 1a. Soil parameters at the Luochuan site under conventional practice as input for the CoupModel

Soil depth (cm)	K_{sat} (cm day^{-1})	θ_s (cm^3 cm^{-3})	θ_r (cm^3 cm^{-3})	Wilting-point (cm^3 cm^{-3})	λ –	ψ_a (kPa)
0-5	1000	0.49	0.06	0.13	0.19	0.29
10-15	1400	0.48	0.06	0.13	0.20	0.33
20-25	700	0.47	0.06	0.14	0.19	0.41
40-45	700	0.40	0.05	0.14	0.14	0.56
60-65	400	0.40	0.05	0.14	0.14	0.46
80-85	448	0.41	0.05	0.16	0.14	0.47
100-105	530	0.41	0.05	0.15	0.16	0.73
120-125	700	0.45	0.03	0.14	0.16	0.71
150-155	500	0.43	0.03	0.15	0.17	1.59
200-205	1000	0.44	0.03	0.14	0.29	3.03

The model was first calibrated using data from a three-year field experiment (Paper IV). Secondly, long-term (45-years) simulations, based on parameters from calibration and daily historical climate data (1956-2000), were run to evaluate the sustainability of various soil management strategies on the partitioning of the water balance and yield of winter wheat at Luochuan (200 km northwest of Heyang) (Paper V). The long-term simulation study included totally seven treatments; conventional management, mulching and fallow crop (Fallow-30d) as carried out in the field experiment for model calibration, two additional fallow crop treatments where the fallow crop was harvested 15 days (Fallow-15d) respective 45 days (Fallow-45d) before sowing the wheat, and two treatments with conventional management, where the soil hydraulic properties had been changed to values found for a compacted (20 % by volume) soil (Paper II) respective a soil with high (3 %) organic matter content. (HOM) (Paper III). The simulated soil compaction was extended to a depth of 45 cm, and the HOM simulation included increased organic matter content in the top 15 cm of the soil. Soil water retention curves and saturated hydraulic conductivities used in these simulations were obtained from laboratory measurements; unsaturated hydraulic conductivity was derived from the Mualem model combining Brooks-Corey's parameters (Eq. 3) from soil water retention and saturated hydraulic conductivity. The corresponding soil hydraulic parameters for the conventional management, compaction and HOM treatments are presented in Table 1. During the simulation period (1956-2000) the soil properties were kept constant, and no nutrients limitation was assumed.

Table 1b. Soil parameters at the Luochuan site following changes from conventional treatment to compaction and high organic matter treatments as input for the CoupModel

Soil depth (cm)	K_{sat} (cm day^{-1})		θ_s (cm^3 cm^{-3})		λ -		ψ_a (kPa)	
	Com.[a]	HOM[b]	Com.	HOM	Com.	HOM	Com.	HOM
0-5	300	-[c]	0.47	0.55	0.17	0.20	2.00	0.18
10-15	400	-	0.47	0.54	0.14	0.21	3.15	0.29
20-25	300	-	0.45	-	0.15	-	2.50	-
40-45	300	-	0.40	-	0.13	-	2.50	-

[a] Compaction treatment

[b] High organic matter treatment

[c] Values that were the same as for the conventional treatment

Analytical methods

Water balance

The field water balance can be written as:

$$P = E + T + D + R + \Delta S + E_i \tag{5}$$

where P is precipitation, E is soil evaporation, T is crop transpiration, R is surface runoff, D is deep percolation below the root zone, ΔS is the change in soil water storage and E_i is evaporation from intercepted rainfall. In this study surface runoff was zero because the topography was flat, and E_i was neglected because it was quite constant and constituted a small proportion of the water balance compared with the other terms. ΔS can be either positive or negative. Therefore, the water balance was calculated as:

$$P - \Delta S = E + T + D \tag{6}$$

Water use efficiency

Water use efficiency (WUE_g or WUE_b) was defined as:

$$WUE = \frac{Y}{ET} \quad (7)$$

where WUE_g or WUE_b represents water use efficiency for the grain or biomass yield (kg m^{-3}), Y is the grain or biomass yield of the wheat, respectively, and ET is evapotranspiration during the wheat season.

Fallow efficiency

The percentage of rainfall stored in the soil profile during the fallow period was designated fallow efficiency and expressed as:

$$FE = \frac{\Delta S}{P_f} \times 100 \quad (8)$$

where FE is fallow efficiency (%), ΔS is the change in soil water storage during the fallow period (mm) and P_f is precipitation during the fallow period (mm).

Statistical analysis

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

Results and discussion

Soil hydraulic properties

Hydraulic properties of loess soils at two sites (Mizhi and Heyang) were measured using undisturbed soil cores (Paper I). The resulting soil water retention curves showed that the two soils were relatively homogeneous throughout their profiles (Fig. 2). However, there was a large difference in the slope of the soil water retention curves between the two soils; the parameters λ and n from the Brook-Corey model were in the ranges 0.14 - 0.20 and 1.15 - 1.21 for the Heyang soils, compared to 0.72 - 0.95 and 2.09 - 2.29 for the Mizhi soil. These findings indicate that the pore size distribution was not even in the Mizhi soil, in which most water loss occurred between about 7 and 40 kPa (reflecting large n or λ values), while the pore size distribution was more even for the Heyang soil. Moreover, the water content at wilting point (1500 kPa) was several times higher in the Heyang soil (16.7% average across all depths) than in the Mizhi soil (4.0 %) due to the difference in their clay contents (Paper I).

The saturated hydraulic conductivity was similar at all measured depths (six depths from the 0 to 100 cm profile) between the two soils; 62 ± 14 (SE) (Heyang) and 60 ± 8 cm day^{-1} (Mizhi) across their soil profiles, but there were larger variations in the Heyang soil than in the Mizhi soil. Stotle et al. (2003) recorded saturated hydraulic conductivities for the surface layer of cropland ranging from 43.3 to 86.4 cm day^{-1} using the constant head method; comparable to our results of 63.5 and 92.3 cm day^{-1} for the surface layers at Mizhi and Heyang, respectively. The rather high saturated hydraulic conductivities of the loess soils should favour rain infiltration.

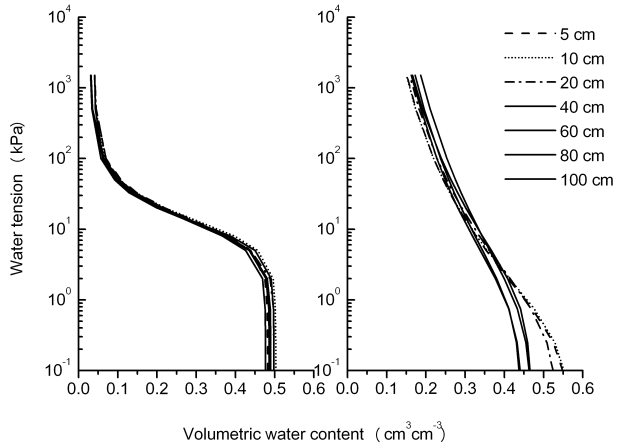

Fig. 2. Soil water retention characteristics of soils at Mizhi (left) and Heyang (right) at various depths.

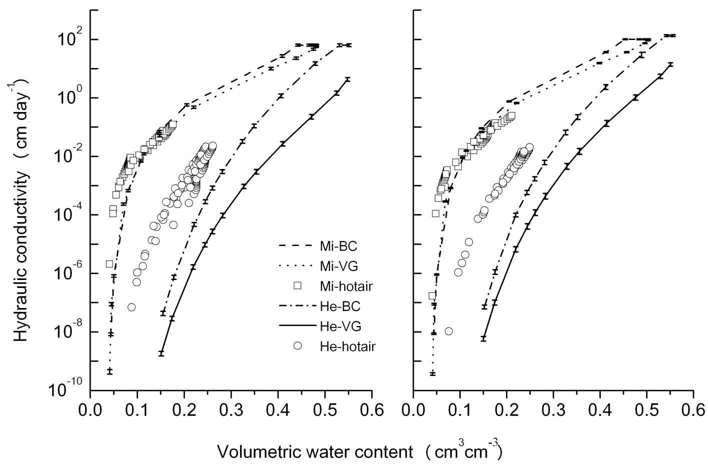

Fig. 3. Unsaturated hydraulic conductivities of the 0 - 5 cm (left) and 10 - 15 cm (right) soil layers at the Mizhi (Mi) and Heyang (He) sites according to the Brooks-Corey (BC) and van Gneuchten (VG) models and the hot-air method. The BC and VG values were calculated for all combinations of measured saturated hydraulic conductivities and soil water retention curves. Vertical bars indicate ± one standard error.

The unsaturated hydraulic conductivity for the top 0-5 and 10-15 cm depths for both of the sites are shown in Fig. 3. The conductivities for the deeper layers at each site were similar to those of the top layers. For the common range of water contents (0.15 - 0.48 $cm^3 cm^{-3}$), the ranges of unsaturated hydraulic conductivities (Brooks-Corey model) were 4.4 $\times10^{-8}$ - 15.1 cm day^{-1} and 7.0$\times10^{-2}$ - 63.5 cm day^{-1} for the surface layers and 7.3 $\times10^{-8}$ - 30.1 cm day^{-1} and 9.1$\times10^{-2}$ - 101 cm day^{-1} for the subsurface layers at the Heyang and Mizhi sites, respectively. The $K(\theta)$ values were much higher for the Mizhi soil than for the Heyang soil at the same soil water content according to both the model predictions and data acquired by the hot-air method; the largest difference being more than six orders of magnitude according to the Brooks-Corey model. Thus, there is a higher likelihood of rapid water loss through evaporation at the Mizhi site, and crops could be more likely to be subjected to water stress there, even though K_s and plant available water (between wilting point and 33 kPa) values were similar for the two soils (0.106 at Mizhi and 0.109 $cm^3 cm^{-3}$ at Heyang).

The results obtained using the various methods of measuring soil hydraulic properties differed in several, systematic ways. The laboratory core method gave higher soil water retentions at low tensions than the field internal drainage method, whereas saturated hydraulic conductivities derived using the laboratory core and Guelph permeameter methods were similar, but lower values were predicted by a pedo-transfer function. The unsaturated hydraulic conductivities obtained from the Brooks-Corey model were closer to the field measurements than those from the van Genuchten model. These comparisons provide useful indications of the methods that are likely to provide the most reliable inputs for simulations under various conditions.

Effects of soil management on soil hydraulic properties

Compaction

The effects of soil compaction on hydraulic properties varied from soil to soil (Paper II). The low level of compaction (C1) did not significantly affect the water retention of the Heyang soil (from either depth), due to the large variations between replicates, caused by natural field variations and the soil management regime (Fig. 4). Similar results have been found for several soils in different landscapes by Green et al. (2003). This implies that our low compaction level (C1) was within the range of normal field variation. However, the high level of compaction (C2) significantly decreased pore volumes with equivalent pore diameters of > 150 µm in the surface layer, and ≥ 60 µm in the subsurface layer (Fig. 4), which directly correlated to saturated flow (Pagliai et al., 2003). Tarawally et al. (2004) reported that compaction significantly reduced the pore volume to equivalent pore diameters of > 50 µm in a Rhodic Ferralsol. The significant reduction in total porosity due to compaction (C2) would influence air exchange and the reduction in large pores would influence root development since the growth of feeding roots requires pores ranging from 100 to 200 µm in diameter (Tippkotter, 1983). The water retention of the Mizhi soil was significantly influenced by compaction across a wider tension range (0-8 kPa) than the Heyang soil (0-5 kPa), for both depths, and there was a significant difference between the two compaction treatments (Fig. 4). Nevertheless, effects of soil compaction for the two soils were still only pronounced below tensions of 100 kPa. These findings are consistent with expectations, since the amount of water retained at low matric tensions (0-100 kPa) depends on capillarity and the pore size distribution, both of which are strongly affected by soil structure at low suctions. At high suctions (100-1500 kPa) water retention is more influenced by soil texture and specific area (Hillel, 2004). This implies that the compaction levels in our study did not affect the textural pores, but significantly changed the structural pores, which form the main functional environment for plant roots.

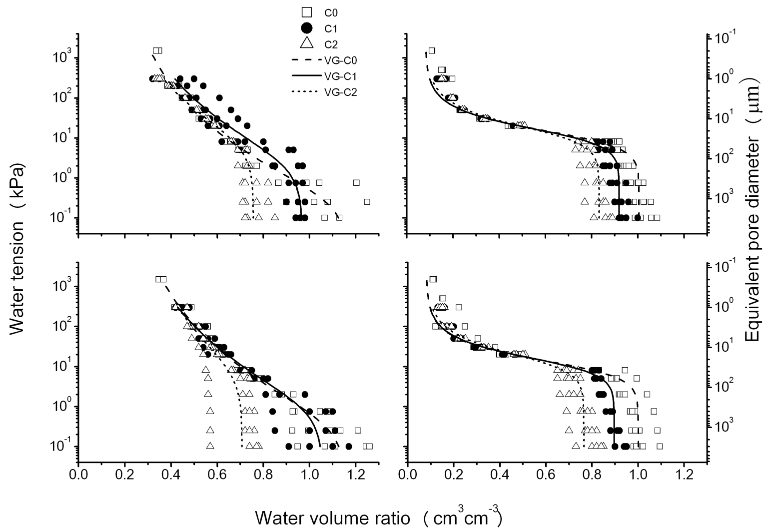

Fig. 4. Soil water retention curves at different levels of compaction (C0, 0%; C1, 10%; and C2, 20%; VG, fitted by the van Genuchten model) of soil from the Heyang (left panel) and Mihzi (right panel) sites for the 0-5 cm (upper) and 10-15 cm (lower) soil layers. The same symbols indicate replicates.

Saturated hydraulic conductivities (K_s) were significantly reduced by the highest compaction level for both sampled layers of the Heyang soil, but no difference was observed in this respect between the C0 (control) and C1 treatments. K_s values decreased with increasing soil compaction for both layers of the Mizhi soil. The K_s values following the C2 treatment were only 18 % and 8 % of the corresponding values for the C0-treated surface and subsurface layers from Heyang, respectively. In contrast, K_s values following the C2 treatment of the Mizhi soil were equivalent to 36 % and 28 % of the C0 treatment values for the respective soil layers. These results were consistent with the changes in the water retention curves discussed above. However, the extents to which the compaction levels reduced K_s and saturated water volume ratios imply that the Mizhi soil was more sensitive to low levels of compaction than the Heyang soil, but less affected by high levels of compaction.

Unsaturated hydraulic conductivities were not affected by the soil compaction levels tested, for either the Mizhi or Heyang soils. However, the unsaturated hydraulic conductivity of the Mizhi soil from both depths tended to be lower following the C2 treatment than following the C0 treatment. Stenitzer and Murer (2003) reported similar changes in hydraulic conductivity between compacted and non-compacted soil at tensions >10 kPa in tests with a loamy silt soil. Sillon et al. (2003), however, found that the compaction treatment gave a higher value in the dry soil moisture range (water volume ratio < 0.3 cm^3cm^{-3}) and no difference in the wet range for a loess soil. It is difficult to compare results from different experiments due to variations in the soils and compaction efforts used. However, unsaturated hydraulic conductivity depends on the continuity of the small pores within soil fragments under certain moisture conditions (Guerif et al., 2001). Thus, it seems reasonable to conclude that the treatments did not affect the unsaturated hydraulic conductivities at either site in our study because there were no significant differences among treatments at pore sizes < 60 μm for the Heyang soil and at pore sizes < 15 μm for the Mizhi soil. The water volume ratio corresponding to our measured unsaturated hydraulic conductivity was beyond the range where compaction had significant effects on pore sizes and spaces. Therefore, hydraulic conductivity should be the same among treatments at the same water volume ratio.

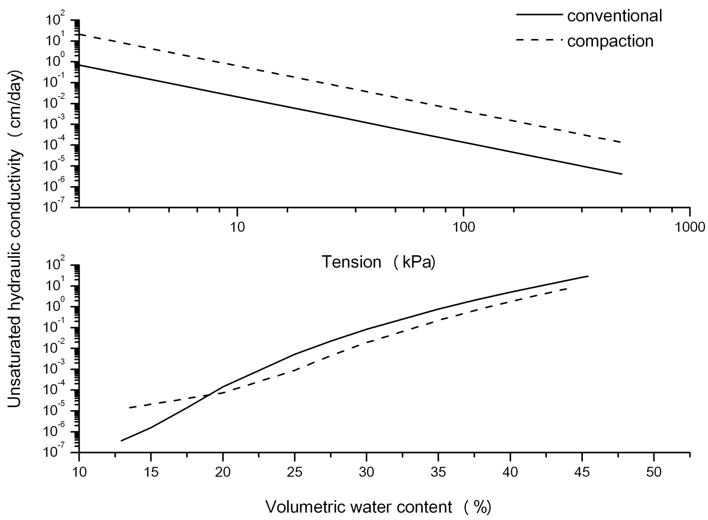

Fig. 5. Unsaturated hydraulic conductivity at the Heyang site according to the Book-Corey model as functions of tension (upper graph) and volumetric water content (lower graph) following the conventional and compaction treatments at 0-5 cm depth.

One point that should be noted is that the common way to present water retention data,. or the hydraulic function is as volumetric water content versus tension ($\psi(\theta)$) or conductivity ($K(\theta)$). In such cases the parameter λ from the Brooks-Corey model, for example, differed between compacted and non-compacted treatments and unsaturated hydraulic conductivity ($K(\theta)$) would be higher in the conventional than in the compacted treatment (Fig. 5). However, the unsaturated hydraulic conductivity was higher in compacted soil than in non-compacted soil when expressed as a function of tension (*K(ψ)*). Moreover, the hydraulic conductivity was similar when the results were expressed as water volume ratios (*K(υ)*) (Paper II).

Organic manure

After 13 years annual application of manure in the long-term experiment at Yangling, the soil organic matter (SOM) content was 2.4 times higher than in the control treatment at the surface layer (0-10 cm) and 1.6 times higher in the subsurface layer (10-20 cm) (Paper III). The soil water retention was increased at both soil depths relative to the control treatment ($P \leq 0.1$); by 13 to 32 % for the 0-5 cm layer at tensions ranging from 0 to 300 kPa and by 5 to 19 % for the 10-15 cm layer from 0 to 2 kPa (Fig. 6).

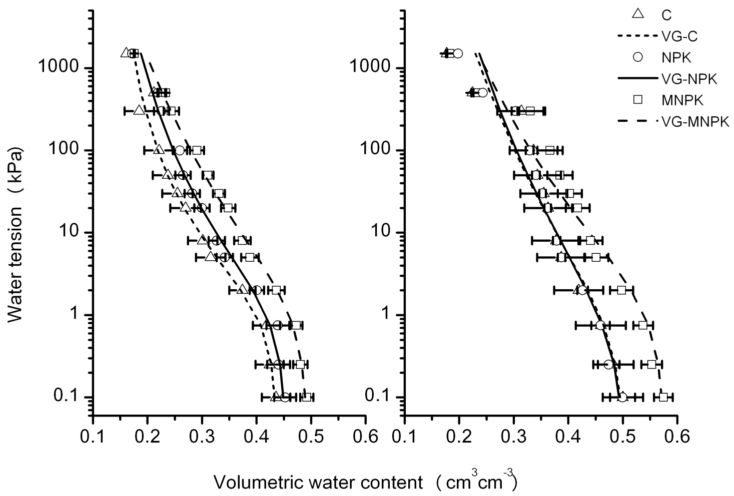

Fig. 6. Soil water retention characteristics of the surface layer (0-5 cm, left) and the subsurface layer (10-15 cm, right), at the Yangling site after 13 years treatment with NPK or organic manure and NPK (MNP) as compared with no treatment (c). Vertical bars indicate ± one standard error.

These findings are consistent with results from other researchers who have reported positive responses of soil water retention to manure addition across a wide range of water tensions (Unger and Stewart, 1974; Schjonning et al., 1994; Obi and Ebo, 1995; Nyamangara et al., 2001). The manure-NPK (MNPK) treatment increased the volume of both large and small pores, thereby improving water retention across a wide tension range for the 0-5 cm layer, but only increased the abundance of large pores at 10-15 cm depth. On the other hand, saturated hydraulic conductivity did not show any significant differences among treatments on the sampling dates, due to the large variations in the data. Similar results were reported by Well and Kroontje (1979), Shirani et al. (2002) and Wu et al. (2003). Miller et al. (2002b) also found that the effects of applying manure on saturated conductivity were highly variable on both dryland and irrigated land. In contrast, substantial increases in saturated conductivity due to adding manure have also been found (Mbagwu, 1992; Obi and Ebo, 1995; Schjonning et al., 2002; Arriaga and Lowery, 2003). Saturated water flow in soil is dominated by the flow in macropores (Lipiec and Hatano, 2003). In our soil the clay and organic carbon contents were relatively high and water flow in cracks and macropores may have made by far the strongest contributions to overall water flow, thereby masking the effect of SOM on saturated water flow and any potentially significant differences between the treatments. Furthermore, we did not find any significant temporal variation in the K_s values of soil that were given the MNPK treatment in the present study. The unsaturated hydraulic conductivity ($K(\theta)$) was reduced by the MNPK treatment when the soil was relatively wet (>0.2 cm^3cm^{-3}) at 0-5 cm depth, and was unaffected at 10-15 cm depth, which was consistent with the water retention curve. Measurements of unsaturated conductivity by Miller et al. (2002b) were within very low suction ranges (0.3-1.0 kPa) and yet they did not find any significant differences among treatments, probably because water transport at low suction would be dominated by flow in relatively large pores. After manure addition, soil physical conditions changed through reductions in the bulk density and increases in water retention. This combined effect of manure treatment would lead to deeper penetration of infiltrating water, but lower unsaturated conductivity at the surface because of the less dense soil at the surface (Unger and Stewart, 1974). Hence, the effects of manure inputs on unsaturated conductivity were related to the applied rate and soil moisture status.

Model calibration

The CoupModel based on physical parameters was calibrated against measurements of soil water content, leaf area index, plant height and wheat yields from a three-year field experiment (Paper IV). The model predicted the timing of soil moisture changes under all treatments reasonably well. The regression coefficients, R^2, ranged from 0.52 to 0.97, and in general the lower values were for the upper 10 cm depth. In most cases the model predicted higher water contents than the measured values, with differences between the simulated and measured mean values ranging from 0.08 to 2.07 %. Compared with the upper 10 cm soil layer, the simulated water contents in the deeper layers showed very good agreement with the measured values. The simulated water content at 10 cm was overestimated during wet periods (high peaks), but was similar to the measured values during dry periods. Unsurprisingly, larger discrepancies were found between simulated and measured water contents in the upper 10 cm of the soil, since this layer is easily disturbed by field management practices, such as sowing, harvesting and compaction caused by taking weekly measurements. It should also be pointed out that the TDR sensors were not calibrated for frozen or partially frozen soil, and it was colder during the winter of 2002/2003 than during the other two years (data not shown), thus leading to uncertainties in the TDR readings at the 40 cm depth in the conventional and fallow crop treatments. We did not simulate frozen conditions in the model. Thus, some of the observed discrepancies between the simulated and measured water contents during that winter may have been due to inaccurate TDR calibration. In the simulation we applied lower saturated water contents (Table 1) than those measured in the laboratory (Paper I). This was because lower values of saturated water content were found under field conditions than in the laboratory, so these values were adjusted to fit the dynamics of the soil water changes during calibration.

The simulated winter wheat development (i.e. changes with time in its leaf area index and height) and yields agreed well with the field measurements.

Long-term effects of soil management regimes on water balance and wheat production

Water balance

Long-term simulations showed that different soil management regimes resulted in different levels of soil evaporation, transpiration and deep percolation (Table 2 and Fig. 7). Annual mean soil evaporation accounted for 58-82 % of the water balance, regardless of the management regime, with wheat transpiration being the next largest term at 17-32 %. Fallow crop transpiration and deep percolation made up the remainder of the balance, accounting for 2-12 % and 1-9 %, respectively. The proportion of soil evaporation in this study was higher than simulated results obtained in the Murray-Darling Basin of Australia (50-58 %), but the drainage and runoff were much lower, and the transpiration similar (Keating et al., 2002). These differences can be explained by differences in soil types and climate between the studies.

Compared with conventional practice, mulching led to 12 % less soil evaporation, 5 % higher transpiration and 6 % higher deep percolation (Table 2). Mulching has been found to be similarly effective on a natural grassland in the Southwest of France, where it decreased annual soil evaporation by 5-10 %, while increasing transpiration and deep percolation (Gonzalez-Sosa et al., 2001). The higher deep percolation induced by the mulching/no tillage was attributed to high infiltration rates through interconnected soil pores (Baumhardt and Lascano, 1996; McGarry et al., 2000). However, some studies have found that mulching decreases not only soil evaporation, but also crop transpiration due to the slow growth at low temperatures caused by mulching (Yunusa et al., 1994; Zaongo et al., 1997). However, this effect depends on the soil type, mulching rate and climate during the experimental period.

In contrast, soil compaction gave 12 % higher soil evaporation, 10 % lower transpiration and 2 % lower deep percolation relative to the conventional treatment (Table 2). High soil evaporation and low transpiration under compaction have also been found on sandy and sandy loam soils (Sadrsa et al., 2005). The lower deep percolation was consistent with the results of a field experiment reported by Sharma et al. (1995) and a simulation study described by Stenitzer and Murer (2003). The repartitioning of water balance under compacted soil was caused by alterations in the hydraulic properties – reduced saturated hydraulic conductivity (Paper II) and high $K(\psi)$ values (Tamari, 1994; Richard et al., 2001) – which caused more soil evaporation but hampered downward soil water flux.

Table 2 Simulated annual mean (fallow and wheat season) soil evaporation, deep percolation, wheat transpiration and fallow crop transpiration in relation to water balance defined by Eq. (6) (%)

Treatment	Soil evaporation				Deep percolation				Wheat transpiration				Fallow crop transpiration			
	Mean	Max	Min	C.V.[1]	Mean	Max	Min	C.V.	Mean	Max	Min	C.V.	Mean	Max	Min	C.V.
Conventional	70 a[2]	84	58	9	3 a	18	0	156	27 a	35	15	16				
Mulch	58 b	76	43	13	9 b	32	0	110	32 b	45	22	17				
HOM	68 ae	85	56	9	4 a	20	0	147	27 a	36	15	16				
Compaction	82 c	90	68	6	1 c	8	0	277	17 c	30	10	23				
Fallow-15d	62 df	81	47	11	2 ac	12	0	169	22 d	35	3	29	12	23	1	49
Fallow-30d	65 ef	82	53	10	2 ac	15	0	165	24 ad	35	9	22	7	14	1	57
Fallow-45d	68 ae	86	57	9	3 ac	18	0	161	26 a	35	11	17	2	7	0	70

[1]C.V. means coefficient of variability
[2]Different letters in the same column indicate differences that are significant at the P < 0.05 level (LSD).

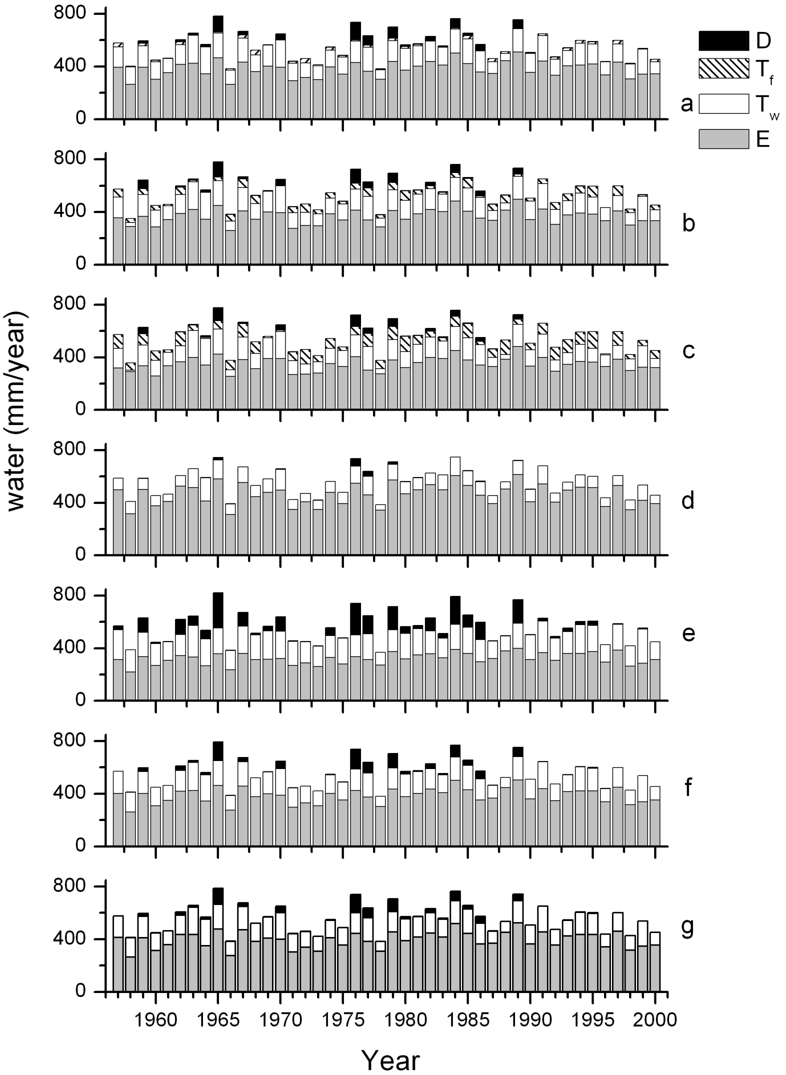

Fig.7. Simulated temporal variation of soil evaporation (E), transpiration (T_w for wheat and T_f for fallow crop, respectively) and deep percolation (D) under various soil management regimes from 1957 to 2000. From the top the treatments are Fallow-45d (a)**,** Fallow-30d (b), Fallow-15d (c), Compaction (d), Mulch (e), High organic matter (HOM, f) and Conventional (g).

The high organic matter treatment positively affected partitioning of the water balance, but the magnitudes of the water balance terms it yielded were not significantly different from those obtained with the conventional treatment (Paper V). Growing a fallow crop decreased annual mean soil evaporation by 2 - 8 %, wheat transpiration by 1-5 % and deep percolation by about 1 % compared with conventional practice (Table 2). The longer the period with a fallow crop, the lower the transpiration in the subsequent wheat season. This was because during the fallow period water consumption (evapotranspiration) in the fallow crop treatment was higher and thus less water was stored than in the conventional treatment (Paper IV). High water consumption by fallow legume crops has also been reported in the central Great Plains of the USA (Vigil and Nielsen, 1998). However, the maximum transpiration of wheat was the same as in the conventional treatment (35 %) and large differences were found in minimum values. This implies that growing a fallow crop for a long part of the fallow period would not affect subsequent wheat transpiration under wet conditions, but would have a severe effect under dry conditions. Hence, a long-lasting fallow crop should not be recommended in dry years unless income from the fallow crop could compensate for the loss of subsequent income from the wheat crop. Under such conditions it may be better to use a crop that can be grown in a shorter part of the fallow period. In the climate of the present study at least 30 days without a fallow crop was needed not to avoid adverse effects on the following wheat production.

During the wheat season mean evapotranspiration was highest in the mulched soil (315 mm) and declined among the other treatments in the following order: HOM (314 ± 58 mm), conventional (313 ± 60 mm), Fallow-45d (310 ± 43 mm), Fallow-30d (301 ± 47 mm), compaction (292 ± 35 mm) and Fallow-15d (290 ± 50 mm) (Paper V). The contributions of soil evaporation to total evapotranspiration corresponded to 42 %, 51 %, 52 %, 51 %, 53 %, 67 % and 55 %, respectively. Higher evapotranspiration has been reported for conventional winter wheat systems in the mid-west of the Loess Plateau in both a 12-year experiment (414 ± 111 mm) (Huang et al., 2003b), and a short-term experiment (390 mm) (Li et al., 2000). However, both of the cited experiments overestimated evapotranspiration because deep percolation was neglected in the water balance estimates. Mulching gave similar evapotranspiration values to the conventional treatment, and similar results have been reported for the maize season in Bushland in the USA (Tolk et al., 1999) and for winter wheat in northwest India (Sharma et al., 1998). However, lower evapotranspiration with mulching relative to the conventional treatment has also been found during the spring wheat season (Yunusa et al., 1994; Huang et al., 2005).

Temporal variation of water balance terms

The temporal variability in soil evaporation and wheat transpiration in each treatment was relatively minor compared to the temporal variability in deep percolation (Table 2 and Fig. 7). For all treatments the coefficients of variation were around 10 % for soil evaporation, less than 30 % for wheat transpiration, but higher than 100 % for deep percolation. The accumulated probability showed that for 50 % of the years deep percolation amounted to less than about 30 mm under mulching, but less than 5 mm for all other treatments (Fig. 8). Growing a fallow crop affected the amount of deep percolation to some extent, but did not substantially affect the probability of its occurrence compared with conventional practice. The amount of deep percolation significantly correlated with yearly precipitation, but was most strongly correlated with fallow rainfall (R^2 = 0.46, 0.28

and 0.63 for conventional practice, compaction and mulching, respectively) (Paper V). To generate deep percolation 405 mm rain was needed with mulching, compared to 504 mm and 589 mm for the conventional and compaction treatments, respectively.

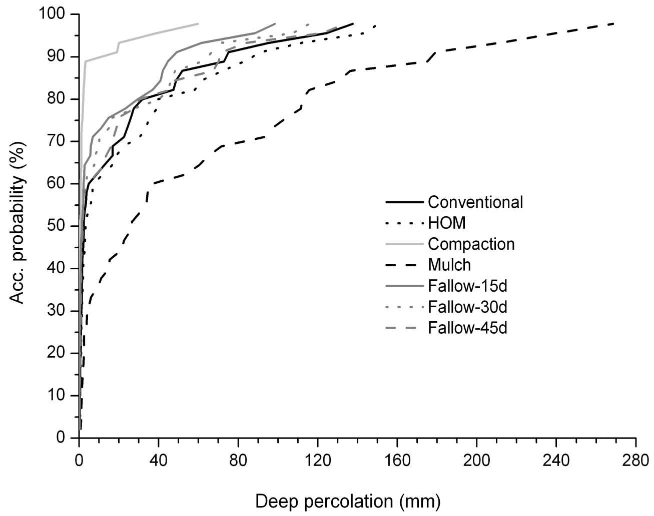

Fig. 8. Accumulated probability of deep percolation occurring under the Conventional, High organic matter (HOM), Compaction, Mulch, Fallow-15d, Fallow-30d and Fallow-45d treatments

Deep percolation is a crucial component of the water balance in the Loess Plateau region. Short-term investigations have found a dry subsurface-layer in the soil profile of agricultural land (Huang et al., 2002) and in a long-term (15-year) experiment it was found that less soil water replenishment occurred in plots subjected to high current levels of fertilization than in unfertilized control plots during fallow periods (Huang et al., 2003a). These results imply that conventional practice reduces the frequency and extent of deep percolation. Our long-term simulations (Paper V) indicate that during the 1960s, 1970s and 1980s, the mean annual deep percolation amounted to 26, 33 and 25 mm, respectively, under conventional practice. However, in the last ten years (1991-2000) annual mean deep percolation amounted to only about 1 mm, implying that there has been little or no potential recharge of groundwater from precipitation during the last ten years. This conclusion was supported by the above experimental results and other studies have shown that the groundwater level is continuously decreasing in the Loess Plateau (Xuan, 1996; Li and Ma, 2004; Zhang et al., 2004).

Mulching nearly doubled the probability of deep percolation occurring compared with conventional practice in our simulations (Fig. 8), indicating that this management practice would increase potential groundwater recharge and environmental sustainability on a regional basis. Mulching reportedly increased groundwater recharge in a clay soil in Australia (O'Leary, 1996). The effectiveness of mulching in this respect is due to the mulch reducing soil evaporation by changing the surface energy balance (Horton et al., 1996), favouring rainfall infiltration (Baumhardt and Lascano, 1996), and improving water storage so more water is transported to deeper soil layers. Therefore, mulching reduced the amount of precipitation required to generate deep percolation compared to the conventional treatment. Another implication of mulching is that it could help conserve water and reduce irrigation frequency in irrigated areas where the hydrological cycle has been degrading as the groundwater table has been drawn down (Kendy et al., 2004; Xu et al., 2005). Due to water over-consumption and climate change, such groundwater depletion has led to the lower reaches of the Yellow River drying up (Xia et al., 2004). However, we should be aware of the effects of soil compaction, caused for example by the use of heavy machinery, which can be worse than conventional practice for a sustainable hydrological cycle. Considering all of the above, deep percolation should be one criterion for evaluating whether a soil management regime is likely to sustain agricultural production and promote a favourable hydrological cycle.

Fallow efficiency

Fallow efficiency significantly correlated with fallow rainfall and rainfall distribution during the fallow period, especially the rainfall in the last month of the fallow period (Paper V). The mean annual fallow efficiency under various treatments ranged from 19 to 38 %. Mulching significantly improved fallow efficiency relative to conventional practice. This is in agreement with results found on a sandy loam in semi-arid Kenya (Gicheru et al., 2004) and on clay loams in Texas (Unger, 1978; Baumhardt and Jones, 2002). Fallow efficiency depends on the duration of the fallow and rainfall distribution, which affect the amount of water lost by soil evaporation. Soil evaporation occurs in two stages (Ritchie, 1972), the first determined by atmospheric demand and the second by available water, which is related to soil hydraulic properties. In our case mulching improved fallow efficiency because summer fallow coincided with the rainy season, causing soil evaporation often to be in the first stage, which was reduced by mulch (Paper IV). However, fallow efficiency was reportedly the same with and without mulching in a place where there was a long fallow period and rain fell in the first half of it (Lampurlanes et al., 2002). Soil compaction gave significantly lower fallow efficiency than the conventional treatment, because it increased hydraulic conductivity ($K(\psi)$) (Fig. 5) and thus higher water losses. Low fallow efficiency in the Fallow-15d treatment was due to the increased transpiration compared with conventional practice. In the Loess Plateau it has been shown that fallow efficiency can account for more than 40 % of the following wheat yield because of low precipitation during the wheat growing season (Li and Shu, 1991). Therefore, the simulations indicate that mulching was the best way to manage the fallow period, followed by HOM treatment and finally a fallow crop with at least a 30-day period of bare soil before planting the winter wheat.

Wheat yield and water use efficiency

The simulated average annual wheat biomass yield ranged from 0.59 to 0.98 kg m^{-2}, regardless of treatment effects, and biomass water use efficiency ranged from 2.00 to 3.09 kg m^{-3} (Paper V). Except for the soil compaction treatment (0.59 kg m^{-2}), the biomass yields of winter wheat were close to those found in a three-year field study in the Loess Plateau (Li et al., 2000). The accumulated probability of the treatments to increase wheat biomass yields relative to the conventional practice showed that mulch increased the yields in 95 % of the years, and by about 20 % in 50 % of the years (Fig. 9). Conversely, soil compaction was the only treatment for which yields were reduced in all years, relative to conventional practice, and the reductions were substantial – amounting to about 30 % in half of the years. However, in short-term field studies of heavy textured soils Radford et al. (2000) reported that soil compaction reduced wheat emergence but not the yield. In our long-term simulation alleviation of soil compaction by shrinking and swelling cycles between rainfall events was not considered. Furthermore, under field conditions field operations can loosen the topsoil and water stress may be slighter than the simulation predicts. Therefore, results of our simulation might overestimate somewhat the side-effect of soil compaction. The treatment in which the fallow crop was grown for the shortest time (Fallow-45d) gave a similar average wheat yield as the conventional treatment, while wheat yields were reduced under the other two fallow crop treatments, and the WUE values followed the same trends. The probability that yield would be reduced by growing a fallow crop was highest when the fallow crop period was longest (i.e. higher for the Fallow 15-d treatment than for the Fallow-30d and Fallow 45-d treatments). The negative effects of long fallow crop periods are in agreement with the findings of Vigil and Nielsen (1998). The simulation results indicate that the viability of using a fallow crop as green manure or fodder depends on the duration of the fallow crop growth.

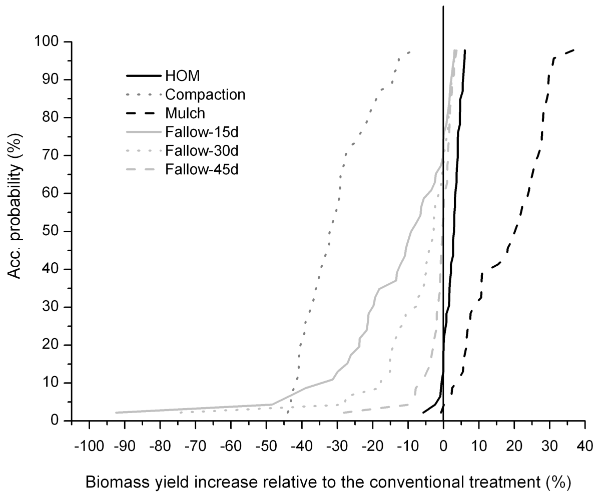

Fig. 9. Accumulated probability of a difference in yield increase between various soil management regimes and conventional practice. The soil management regimes were: High organic matter (HOM), Compaction, Mulching, Fallow-15d, Fallow-30d and Fallow-45d

Conclusions and future perspectives

The soils on the Loess Plateau showed significant variations in hydraulic properties, which were measured by field methods that gave good agreement with the laboratory soil core method. Water retention of soils was weaker in the north part (Mizhi) of the Loess Plateau than in the south (Heyang and Yangling), while unsaturated hydraulic conductivity, $K(\theta)$, was lower in the south. The soils showed similar saturated hydraulic conductivity values. Soil management regimes significantly influenced the soil hydraulic properties.

The CoupModel was suitable to be applied on a loess soil to demonstrate the complex interactions between different processes in the soil-plant-atmosphere system. The long-term simulation showed that soil management strongly influenced the magnitude of the water balance components. The work underlying this thesis showed that mulching was the best of the tested soil management regimes. However, this practice could also cause the formation of a "dry subsoil layer" if the crop density is not controlled. Hence, a further task for the future is to determine the ideal crop density at which both desirable crop yields and water balance partitioning can be maintained. From a water-conserving perspective, the results of these studies indicate that extending mulching to irrigated areas could be an ecologically sound approach. Increasing the soil organic matter content improved soil hydraulic properties and could be another suitable approach provided sufficient amounts of organic matter are applied. Considering all of the factors involved, the duration of the bare fallow should not be less than 30 days (Fallow-30d or Fallow-45d) to maximise the benefits of producing green manure or fodder without interfering significantly with the wheat yield and WUE. Since considerable time is needed to increase SOM by adding green manure (more than three years, Paper IV), use of fallow crop as fodder might be a good choice, leaving the wheat straw as mulch. If a fallow crop is grown with mulching, there is a need to estimate the optimal fallow crop duration.

The severe effects of soil compaction on hydraulic properties and further on the water balance and crop production put an alarm on those similar soils in China. Therefore, much more attention should be paid to investigate and protect land in such respect in order to prevent from the same fate as has happened in many developed countries.

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