Maize residues, soil quality, and wheat growth in China. A review

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REVIEW ARTICLE

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Abstract Crop residue retention is a key component of sustainable cropping systems. In recent years, retention of crop residue is a means of improving soil quality and nutrient capacity and reducing the adverse effects of residue burning. Maize–wheat rotation is a major double-cropping system practiced on more than one fifth of agricultural lands worldwide. Currently, more than 50 % of maize residues are retained immediately after harvesting. In China, this practice has beneficial effects on soil properties and productivity of the succeeding wheat crop. However, increasing the retention of maize residues without proper soil management has also led to a series of concerns, such as short-term nitrogen immobilization, rapid moisture loss, and high susceptibility to freezing during winter as a result of increased soil porosity. Therefore, other practices for maize residue retention are needed to promote wheat growth and the release of nutrients. This article reviews recent developments in China concerning the consequences of maize residue retention on the physical, chemical, and biological properties of soil quality and the growth, productivity, and quality of wheat. Major patterns of maize residue retention are discussed. In particular, this review provides three complementary approaches for maize residue management.

Keywords Maize (*Zea mays* L.) · Reduced tillage · Residue retention · Soil quality · Wheat (*Triticum aestivum* L.)

Content

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1 Introduction

The continued use of chemical fertilizers leads to a continued decline in soil quality and other environmental problems. For example, the application of nitrogen (N) fertilizers is proven to cause low N use efficiency (NUE) in crops and environmental pollution by the accumulation of NO_3–N in the soil (Zhao and Chen 2008a; Zhu et al. 2001). Crop residues are an important source of plant nutrients and organic matter. Long-term residue retention increases soil microbial composition and biomass, promotes soil nutrient recycling, increases the soil organic matter (SOM) content (Liu et al. 2011), improves soil quality, creates a soil regime favorable for root development, and results in higher crop yields (Zhao and Chen 2008a; Zhou et al. 2008). The retention of crop residues has been proven an effective field practice in terms of reducing nutrient inputs (Ma et al. 2003), especially in rainfed conditions (Fig. 1). However, the removal of crop residues from the field is known to hasten the decline in soil organic carbon (SOC), especially when coupled with conventional tillage (Abro et al. 2011). Therefore, residue retention should be strongly recommended in crop production (Wu et al. 2002).

Crop residue retention is an important component of environmental protection; residues with high lignin content contribute to soil carbon sequestration and lower CO_2 effluxes in the soil (Dong et al. 2009; Zibilske and Materon 2005). Residue retention has the potential to mitigate the global increase in atmospheric greenhouse gases (Young 2003). The burning of residues contributes to environmental pollution. Therefore, crop residue retention should be promoted for the improvement of soil quality and the health of the environment.

Maize has a high ratio of straw to grain weight (2:1) (Gao et al. 2009). In 2006, the amount of maize residues in China was 291 mt; maize accounted for 38.2 % of all crop residues, including rice (*Oryza sativa* L.), wheat, sorghum (*Sorghum vulgare* Pers.), and peanut (*Arachis hypogaea* L.). Maize residues contain 2.68 mt N, 1.00 mt P_2O_5, and 4.12 mt K_2O (Gao et al. 2009). In the major production regions of China, maize residue retention accounts for 17.9 to 43.6 % of the total residue, varying with the planting region (Wang et al. 2011b).

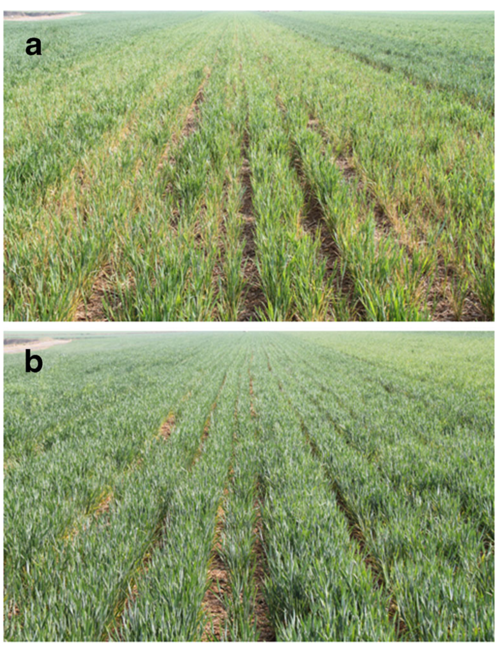

Fig. 1 The long-term effects of maize residue retention on wheat seedling growth under dry-land, rainfed conditions in a wheat–maize rotation system over 5 years. **a** Wheat plants grown in deep tillage without residue retention showing poor seedling growth at the jointing stage. Tillage without residue retention leads to poor soil health in the long term with a low potential for soil moisture conservation. **b** Deep tillage combined with maize residue incorporation, showing improved seedling growth. Tillage with residue retention creates a better quality soil with a high soil water content compared with tillage systems without maize residue retention (**a**) (photo credit: Jisheng Si)

The remaining residue has commonly been used as animal fodder and fuel or is burned directly in the field (Abro et al. 2011; Ma et al. 2003; Wang et al. 2011b). Such burning of crop residues leads to environmental pollution and the loss of resources.

The maize–wheat rotation is a major double-cropping system in China. In recent decades, wheat has been harvested using a combine with residue covering the soil. The practice of wheat residue retention is widely accepted by small-scale farmers because the wheat residue is easily shattered during harvest, is rapidly decomposed because of frequent rainfall during the maize growing season, and produces many beneficial effects on crop growth. Therefore, reduced or zero tillage is traditionally adopted for maize planting after the wheat harvest. The popularity of combined harvesting that allows residues to be left directly on the field has grown in recent years due to a policy that prohibits residue burning in the field. As fewer residues can be used for fodder due to a sharp decrease in the use of draught animals and because the use of gas as fuel instead of residue has been rapidly adopted, the practice of maize residue retention has been greatly expanded in China (Dong et al. 2009). Thus, the effects of maize residue retention on the properties of soil, the growth of wheat, and the sustainability of the field ecosystem are worth examining.

2 Patterns of maize residue retention

Maize residue retention is generally divided into two major patterns. The first is the conventional tillage system, in which the residue is chopped or crushed to some degrees using a harvester and incorporated into the soil via moldboard plowing or rotary tillage. Moldboard plowing disturbs the soil to a depth of 25–30 cm. This practice is followed by harrowing, which almost completely incorporates maize residues into the soil. For rotary tillage, the soil is disturbed to a 12- to 20-cm depth. This tillage is followed by harrowing, through which partial crop residues are incorporated. Following these practices, wheat is generally drill sown with a uniform spacing of 20–22 cm. Rotary tillage has been widely adopted in recent years due to the lower labor inputs required. The second major pattern is conservation tillage, which includes reduced tillage (Fig. 2) and zero tillage. In these practices, the residues are chopped at harvest and left to cover the soil. Reduced tillage can be accomplished by partial rotary tillage (8–12 cm in width) with a 24- to 28-cm zone of zero tillage that is used as spacing, followed by sowing and immediate compacting. Zero tillage is achieved by sowing wheat with a no-till planter without any soil disturbance. In China, reduced tillage practices have been gradually adopted as an alternative to conventional tillage.

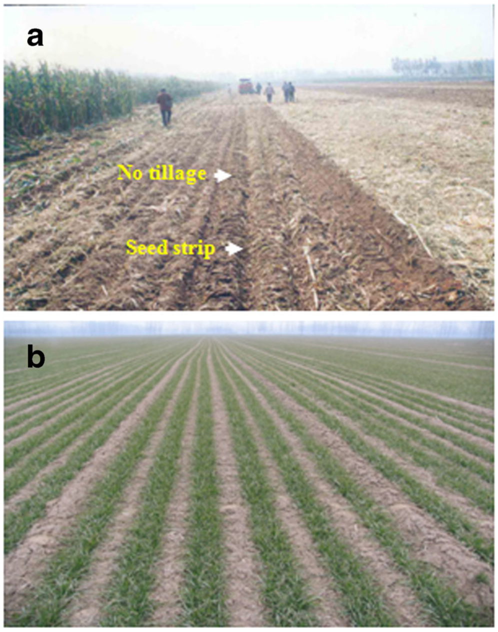

Fig. 2 **a** Direct wheat sowing immediately after maize harvest using a reduced-tillage drill with maize residue retention. Soil strips with a width of approximately 8–12 cm are tilled to a depth of approximately 20 cm. Two rows of wheat were planted with a narrow spacing. Approximately 24–28 cm is not tilled in the wide spacing. The drill can accomplish partial tillage, sowing, the application of fertilizers, and soil compaction simultaneously. Therefore, this practice enhances timely planting that takes full advantage of soil moisture. When tilling the seed strip, the drill can cut the residue a second time following the cutting of maize using combined application, thereby accelerating the decomposition of residues. **b** Wheat seedling growth, showing the planting configuration of wheat using the reduced-tillage drill (photo credit: Jisheng Si)

3 Effects on soil quality

3.1 Physical and chemical characteristics of soil

The incorporation of maize residues into the soil via tillage has the potential to reduce the soil bulk density and increase the SOM content, SOC storage, soil porosity, percentage of soil macroaggregates, and availability of N and K (Bai et al. 2011; Wu et al. 2002; Fan and Liu 2005; Ma et al. 2003; Zhou et al. 2008; Wang et al. 2011a). Controversial results have been observed for soil P availability. Jiang et al. (2011) reported that residue retention over 2 years could increase the total P content by 10 %. Similar results were observed by Bai et al. (2011) and Hu et al. (2013). However, Wang et al. (2011a) found that the total P content at the 0- to 10-cm profile decreased by 6.8 and 6.3 mg kg^{-1} after 11 and 15 years of residue retention, respectively. Furthermore, You et al. (2012) observed that residue retention increased the total P content while rapidly decreasing the available P. The decline in P content may be caused by the higher P uptake by wheat plants and the higher remobilization efficiency of P (Shen et al. 2012); these factors decrease the relative soil P content (You et al. 2012).

The beneficial effects of the retention of maize residues on soil quality are greater than those observed when the same amount of pig manure or cattle feces is applied (Gong et al. 2008; Wu et al. 2002; Zhou et al. 2008). The improvement in soil quality is positively related to the amount of residues at a range of 0–6,750 kg ha^{-1}, especially when combined with the application of fertilizers (Lao et al. 2003). Interestingly, the soil pH significantly decreases with maize residue retention (Bai et al. 2011), largely due to the organic acid and CO_2 derived from the residues by microbial growth; the decreased soil pH results in the greater availability of soil nutrients and an improvement in wheat growth, particularly in alkaline soils.

Under no-till conditions in northern China, 5 years of residue mulching increases the subsoil porosity by 13.8 %, increases the topsoil water-stable aggregate (≥0.25 mm) by 104.5 %, increases the soil alkali-hydrolyzable N content by 23.3 %, and increases the topsoil SOM content by 31.4 % compared with soils without mulching (Niu et al. 2007). Moreover, the soil moisture capacity is 5.6–17.0 % higher under zero tillage than under other combinations of tillage and residue management (Niu et al. 2007). Under rainfed conditions, mulching with 6,000 kg residue ha^{-1} is optimal for soil moisture retention and the maintenance of a better soil temperature regime throughout the wheat-growing season compared with other management practices (Yu et al. 2007). Residue mulching or incorporation into soil by tillage significantly improves soil water availability and WUE (Jin et al. 2013; Su et al. 2007) (Table 1). In this respect, reduced tillage with residue removal does not show any advantages over conventional tillage (Su et al. 2007).

Similar results have been observed by Govaerts et al. (2009) and Anyanzwa et al. (2010). These authors report that, compared with other combinations of tillage with residue management, no-till practices with residue mulching promote the build-up of SOC in the surface soil and increase the distribution of soil aggregates, increase stability, and increase direct infiltration. These changes allow the crop to trap soil nutrients and water. Residue retention in permanent bed planting

Table 1 Effects of maize residue retention on wheat water use efficiency

Treatment	Water infiltration (mm)	Water consumption (mm)	Grain yield (t ha^{-2})	WUE
Tillage with residue retention	18.1b	235.6a	6.2b	26.3b
Tillage without residue retention	64.3a	214.0b	7.4a	34.4a

Compared with the tillage practice with residue removal, residue incorporation into soil by tillage significantly improves soil water availability, water use efficiency (WUE), and grain yield, largely due to the improvement of water infiltration into soil and decrease in water consumption by wheat plants. Means followed by the same letter within a column are not significantly different by a Tukey test ($P<0.05$). Source: Jin et al. (2013)

increases the soil microbial biomass C, total N, water infiltration, and aggregate stability (Verhulst et al. 2011b). In reduced-tillage conditions, residue retention improves soil aggregation, likely due to the significant increase in the SOC content and the protection of the surface soil. However, reduced tillage without residue mulching does not cause any appreciable effect on the soil aggregation status when compared with conventional tillage practices (Ghuman and Sur 2001). The data presented above indicate that the application of residues may be a dominant factor in the interactions between residue and tillage in dry regions; the effects of residue retention are observed under either reduced or zero tillage practices (Wang et al. 2012; Zhang et al. 2009).

The configuration of crop planting may be another key factor influencing wheat growth. Wheat grown under reduced tillage with wide spacing benefits from improved field air circulation and stronger light penetration (Fig. 3a) than wheat grown under conventional tillage (Fig. 3b). In wheat, reduced tillage practices result in stronger stems (Fig. 4; data not published) and a higher efficiency in reserve remobilization

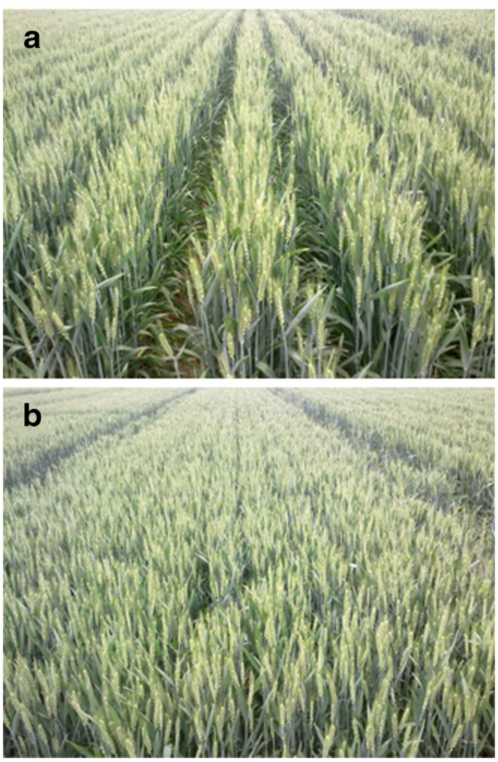

Fig. 3 Comparison of wheat population features between the reduced and the conventional tillage systems with maize residue retention. **a** Wheat plants in the reduced tillage system show improved microclimate characteristics because of the wider spacing (24–28 cm) (see, also, Fig. 2). Wheat plants grown under reduced tillage usually have a greater net photosynthesis rate, more grains per spike, a greater 1,000-grain weight, and higher overall grain yields than plants grown under conventional tillage. **b** Wheat plants grown under conventional tillage with uniform spacing (~20 cm). The wheat plants suffer from decreased field air circulation and weaker light penetration; these factors are unfavorable for wheat development and grain filling

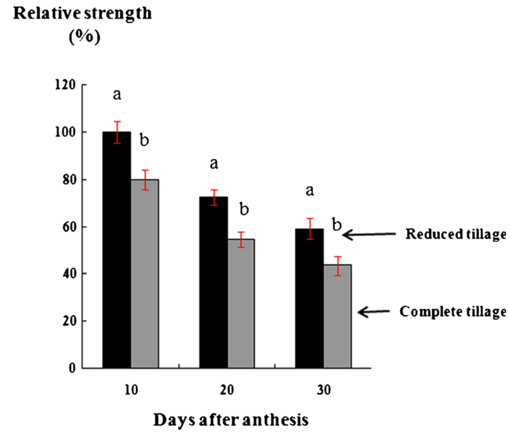

Fig. 4 Comparison of wheat stem strengths between the reduced and complete tillage systems with maize residue retention. Compared with conventional tillage, wheat plants grown under reduced tillage develop greater stem strength; the occurrence of lodging at late stages of grain filling is decreased. Higher stem breakage strength may also promote the remobilization of reserves from vegetative organs to the developing grain

from the vegetative organs to the grain (56.8 vs. 50.6 %; data not published). In reduced tillage systems, the sowing machines manufactured in China can compact the seed strip immediately after seeding and form furrows to collect rainwater into the seeding strip (Fig. 2). This compaction improves the conservation of soil moisture and results in a lower emergence rate but earlier seed germination and better stand establishment (Jia et al. 2010).

3.2 The microbial community

Soil micro-flora activity is considered one of the most important indicators of soil quality; the soil ecology regime therefore contributes to agricultural sustainability (Govaerts et al. 2007). The continuous, uniform supply of C from crop residues serves as an energy source for microorganisms (Govaerts et al. 2007). The resulting increase in the microbial biomass when residues are retained results in increases in the soil respiration rate and the release of CO_2 when compared with residue removal practices (Qiang et al. 2004; Wang et al. 2011c). Given the increases in soil temperature and temperature stability when residues are retained (Yu et al. 2007), the microbial biomass at the tillering stage of wheat were 51.7 and 12.8 % greater when residues were incorporated with tillage and when residue mulching occurred without tillage, respectively, compared with tillage practices without residue retention; the increase in microbial biomass was mainly attributed to the significant increase in bacteria population (Liu et al. 2011). Fan and Liu (2005) found that the soil microbial biomass, particularly P-dissolving bacteria, greatly increases in reduced tillage systems with residue retention. However, the authors also reported that no significant difference in the soil microbial biomass was observed in conditions under which residues were retained compared with conditions under which residues were removed before deep tilling. Considering that bacterial growth is significantly greater in soil with residue retention, the increase in the microbial biomass is mainly attributed to the increase in the bacterial population (Liu et al. 2011). This situation may be true in the early phases of residue decomposition. Cui et al. (2005) reported that microbial diversity and activity increase in residue retention systems, with bacteria dominating; as the residue decomposes, the fungal community tends to increase, and the bacteria/fungi biomass ratio decreases. The variation in the composition of the microbial community results from the change in the chemical components of the residue (Bastian et al. 2009) and the competition among diverse microbes (Cui et al. 2005). In the initial phases of decomposition, bacteria can grow rapidly on easily available compounds that are present in the freshly added plant residues. Fungi, which grow more slowly than bacteria but can decompose more recalcitrant material, are dominant in the later stages of decomposition (Poll et al. 2008).

When residues are retained, the introduction of microbes has been shown to be beneficial to soil quality and wheat growth. When inoculated with *Streptomyces microflavus* and *Aspergillus niger*, residue retention enhances the decomposition of maize residues and increases the microbial biomass of C, N, and P; the release of N and P from the straw increases and promotes soil nutrient availability and the growth and productivity of wheat (Zhang et al. 2005a,b). When residues are inoculated with fungi, the SOM content and the mineralization of N, P, and K in the residue increase. These factors promote wheat growth and grain yield (Li et al. 2001). In addition, this practice enhances the activity of soil urease and phosphatases and promotes the early peaks in activity, leading to increased soil microbial biomass (Zhang et al. 2006). When residues are treated with biocontrol actinomycetes (*Streptomyces* sp.), the occurrence of sharp eyespot (*Rhizoctonia cerealis*) decreases significantly. The presence of actinomycetes inhibits the onset of disease; as a consequence, the grain yield has been shown to increase by 23.1 % ($P<0.05$) (Wang et al. 2011c).

3.3 Soil enzymes, C storage, and C sequestration

The activity of soil enzymes is a key indicator of soil quality and is mainly influenced by the activities of soil microbes and animals, the SOM, and plant growth. The incorporation of maize residues increases the activity of soil urease (Lao et al. 2003), phosphatases, catalase, and convertases, and more significant changes are associated with deep tillage than with rotary tillage (Li et al. 2006a; Yang et al. 2011). In cinnamon soil, the activities of ureases, phosphatases and, on some occasions, catalase and convertase are higher during the entire wheat growing season when residues are retained rather than removed (Zhang et al. 2005b; Zhang et al. 2006). However, the effects of these enzymes may vary with the soil texture, the climate during the cropping season, and the tillage methods used. In semiarid climates, the activities of these four soil enzymes increased when the amount of residues increased from 0 to 9,000 kg ha^{-1}. Enzyme activities showed a significantly positive correlation with the soil organic matter and total N (Gao et al. 2012). Residue retention produced significantly higher activities of ureases and catalase when deep tillage rather than rotary tillage was used (Yang et al. 2011). Greater N inputs (420 kg N ha^{-1}) promoted the effects of residue retention on the activities of soil enzymes (Gao et al. 2012). Residue retention increased the urease activity by 35.9 % in lime concretion black soil (Xia et al. 2013) at anthesis; however, the urease activity only increased by 11.3 % in loam soil (Yang et al. 2011). A no-till system with residue retention increased the activities of β-glucosidase, *N*-acetyl-β-glucosaminidase, protease, and urease compared with moldboard plowing without residue retention. These increases in enzyme activities were more pronounced in the sand fractions of the Haplic Cambisol soil than in the silt and clay fractions (Qin et al. 2010).

Maintaining a satisfactory SOC content sustains soil fertility and the productivity of agroecosystems. Soil with residue retention can store some of the atmospheric CO_2 fixed by plants and mitigate greenhouse gas emissions. Total C content and SOC increased by 2.04 and 1.56–2.50 g kg^{-1}, respectively, when a no-till with residue mulching system was utilized for 7 years compared with other tillage methods without residue retention (Yang et al. 2010). A 12-year field experiment indicated that topsoil (0–20 cm) C storage significantly increases with the straw retention rate, and the amount of residue retention positively affects the topsoil C-sequestration effect of chemical fertilization (Lou et al. 2011). Generally speaking, the significant increase in C storage was only observed in surface soil during long-term straw incorporation; over a 2-year period, C storage showed little change (Qin et al. 2010; Xu et al. 2011). The increase in C storage may be largely attributed to the reduction in C emissions from the soil and the high C input due to residue retention. Indeed, Qin et al. (2011) found that carbon emissions were reduced by 2.01 kg ha^{-1} day^{-1} compared with soils in which residues were removed. A five-year experiment showed that chopped residue increased C storage in the 0- to 30-cm soil layers, regardless of the tillage regime. This increased C storage was due to a lower burst in soil CO_2 emissions and a higher conversion of C from plant residues into soil microbial biomass (Dong et al. 2009; Zhang et al. 2010). However, Govaerts et al. (2009) reported that reduced C emissions were mainly attributed to the reduction in tillage operations rather than the retention of crop residues. Nevertheless, there is potential to improve C sequestration with residue retention in reduced, zero-tillage, or deep-tillage systems in China. The challenge is to develop appropriate tillage systems and residue management techniques to improve soil C sequestration.

4 Effects on wheat growth, productivity, and quality

4.1 Growth and productivity

Compared with residue removal systems, the retention of maize residues results in significant increases in the activity of scavenger enzymes (SOD and POD) and the net photosynthesis rate (by regulating the Chla content, Chla/Chlb ratio, stomatal conductance, intercellular CO_2 concentrations, and other photosynthesis-associated agronomical and physiological traits). This process results in late plant senescence and an increase in the duration of grain filling, the grain filling rate (Liu et al. 2007; Liu et al. 2008b; Zheng et al. 2009; Zhu et al. 2001), the fertile spikelet number, and the spikelet grain number in both the main stem and tiller spikes (Qu et al. 2011). A fixed-plot field experiment revealed that the incorporation of residues (ca. 7,500 kg ha^{-1}) might increase the dry matter accumulation (DMA; particularly between heading and maturity) and the NUE compared with residue removal systems; a more significant difference is observed when wheat is supplied with ca. 270 kg N ha^{-1} (Zhao and Chen 2008a).

Generally, the yield of wheat when maize residues are retained is greater than when residues are removed (Lao et al. 2003; Liu et al. 2007; Ma et al. 2003; Zhang et al. 2009; Zhang et al. 2010). In a 15-year field experiment on the Loess Plateau, the wheat yield increased by 11.7–97.6 % (with an average across years of 27.6 %) in a zero-tillage system with residue mulching compared with a conventional tillage system without mulching; the increase in wheat yield varied with the annual amount of precipitation (Wang et al. 2011a). The yield increase is largely attributed to the decrease in soil bulk density and increases in water retention, soil moisture, SOM content, alkali-hydrolyzable N content, the available soil K content, the DMA, and the remobilization of reserves to grain (Shen et al. 2012). By contrast, the increase in yield is likely not associated with the tillage pattern (Su et al. 2007). However, results have not always been consistent in various experiments, particularly in tilled fields. Residue retention and the interaction between tillage and residue retention have little effect on wheat growth and productivity (Han et al. 2007); however, the grain yield of wheat varieties with low tillering potential was significantly reduced (Zhang et al. 2011). Under zero-tillage conditions, residue mulching on irrigated lands was found to delay plant re-greening in the subsequent spring, increase the occurrence of leaf chlorosis and wilt, and reduce the DMA, grain yield, and WUE. Mulching does improve the soil quality and the field microclimate; higher soil temperatures occur during tillering, and a lower canopy humidity is observed at later growth stages (Li et al. 2006b; Niu et al. 2007).

Grain decline may occur in some cases due to the following factors: (1) poor soil–seed contact caused by residue incorporation that leads to a reduced uptake of nutrients, reduced seedling and tiller numbers, and ultimately reduced grain yield (Jia et al. 2010); (2) the residues retained on the topsoil or buried in the soil act as a succession of barriers, influencing sowing and stand establishment (Li et al. 2006c); (3) the mulching represses soil warming after winter and therefore influences root viability, soil enzyme activity, and microbial activity (Yu et al. 2007); (4) continuous maize retention over the years usually leads to severe infestations of insect wheat pests; and (5) the release of chemical substances from the decomposing maize residues produces a strong allelopathy on the germination of wheat seeds, seedling growth, and root vigor (Zhang et al. 2007), although the allelopathic effect declines as the residue decomposes (Yang et al. 2005).

The incorporation of residues depresses wheat tillering and tiller development and decreases the DMA before the jointing stage and decreases grain yield, WUE, and NUE under low soil N conditions (Zhao and Chen 2008a; Yan et al. 2011). The beneficial effects of residue incorporation are initially observed at the booting stage, when more than 150 kg N ha^{-1} is applied (Yan et al. 2011). These results may be caused by the following factors: (1) at early growth stages, a higher microbial population results from the rapid decomposition of residues and can actively fix soil N and reduce soil N availability and (2) the incorporation of crop residues with a high C/N ratio immobilizes soil N and reduces its availability to crops (Govaerts et al. 2006; Yan et al. 2011; Zhu et al. 2001). Therefore, the depression of the early growth stages of wheat when residues are retained can be partially overcome by applying high amounts of N fertilizers at planting.

4.2 Wheat quality

Residue retention increases the nitrate uptake efficiency of wheat and increases the grain protein content (Liu et al. 2008a; Zhao and Chen 2008b) and amino acid yield (Liu et al. 2008a). However, this practice has also reduced the wet and dry gluten content of wheat grains, which leads to decreases in the flour precipitation value and the stability of dough (Liu et al. 2008a). These effects may be variety dependent, as the increase in grain protein content generally occurs in high-gluten varieties and the improvement in dough development and stability time is observed in low-gluten varieties (Zhang et al. 2011). Although there is a large body of evidence concerning the effects of residue retention on soil quality and wheat grain yield, little information is available on wheat grain quality either in China or globally (Jiang et al. 2011). In a maize–rice rotation, the retention of maize residues increased the grain protein content; however, this was only observed when low N inputs were supplied compared with residue removal systems, and no differences in the amylase content or the gel consistence were seen (Ge et al. 2013). Therefore, grain quality may be a major topic in future studies.

4.3 Effects on the occurrence of pests and insects

Residues retained on the soil surface introduce residue-borne pathogens; these pathogens, in turn, use the residues as a substrate to multiply. As a consequence, wireworms, white grubs, and mole crickets occur much more frequently between the shooting and heading stages (March to April in China). Non-decomposed residues are considered the principal inoculum sources for *Fusarium graminearum* and *Fusarium culmorum*; *Fusarium* head blight (FHB) severity and deoxynivalenol contamination increased significantly with the density of the preceding crop residues (Blandino et al. 2010). Plowing to a 30-cm depth to bury residues significantly reduced FHB severity (by 63 %), reduced the occurrence of deoxynivalenol (by 80 %), and decreased the deoxynivalenol concentration in wheat grain compared with conservation tillage systems (Blandino et al. 2010).

Extract from decomposing residues shows inhibitory effects on *R. cerealis* Vander Hoeven, *Gaeumannomyces graminis* (Sacc.) Arxer Oliver, and *Bipolaris sorokiniana* (Sacc.) Shoem (Zhang et al. 2007). Thus, residue retention may inhibit the occurrence of some types of diseases.

5 Complementary approaches to maize residue management

Residue retention leads to problems such as drought and freezing stresses (resulting from high soil porosity), the immobilization of inorganic N, and the inhibition of wheat seedling growth. Maize residue management combined with tillage is a major challenge for wheat producers, especially in northern China where maize–wheat rotation is a common practice. Rapid residue decomposition may overcome some of these disadvantages. However, many biotic and abiotic factors, such as soil moisture, temperature, and the addition of nutrients, drastically affect residue decomposition in the soil. Therefore, better strategies for the utilization of crop residues are urgently needed to promote residue decomposition while improving soil fertility and quality.

5.1 Cellulase treatment

Treatment with cellulase promotes residue decomposition (at a rate of 8.01–14.04 % higher than without treatment) and the mineralization of the nutrients contained in the residue; the available N, P, and K in the soil are 6.50, 4.27, and 47.97 mg kg^{-1} higher, respectively, with cellulase treatment than without cellulase treatment (Han et al. 2005). However, these results were obtained under lab conditions. These practices need to be investigated in the field.

5.2 Application of inorganic N

A C/N ratio of 18:25 seems to be most suitable for microbial activity. The retention of maize residues results in a high soil C/N ratio, which restricts the decomposition of residues and leads to net N immobilization (Abro et al. 2011; Alijani et al. 2012). Some reports have recommended the application of additional inorganic N to amend the C/N ratio to an appropriate level; this practice has profound effects on the decomposition of maize residues, CO_2 evolution, C mineralization, and soil properties for subsequent crops (Abro et al. 2011). In China, it has been observed that maize residue retention combined with N fertilization results in increases in the SOM content, field water holding capacity, soil porosity, nutrient availability (Gong et al. 2008), WUE, NUE (Yan et al. 2011), grain yields (by 7.1–11.1 %), and N harvest index (by 6.2–16.7 %) compared with no N fertilizer treatment (Zhao and Chen 2008a, 2008b). As a result, the NO_3^- residue in the 0- to 200-cm soil profile declined significantly at maturity (Zhao and Chen 2008b). The wheat yield increase observed when residue retention and N fertilization are combined is mainly due to a higher net photosynthesis rate, greater leaf transpiration, and a larger number of spikes per unit area (Liu et al. 2007). The DMA is lower when N is not applied due to the lower NUE and the decrease in soil water content (Verhulst et al. 2011b).

Mineral-N inputs increase the initial decomposition efficiency, possibly due to a shift in the decomposer community composition toward organisms that are more efficient but have a greater N requirement (Ågren et al. 2001). The increase in the initial decomposition efficiency has been observed in a lab incubation study in certain soil types; however, the authors also reported a decrease in the residue decomposition rate during the second phase (Chen et al. 2007). The mechanisms of the suppressive effects of N at the late stage are not fully understood, although some have been suggested and partly proven. Fog (1988) suggested that ammonia suppresses the production of enzymes required for the degradation of recalcitrant lignocellulose. Carreiro et al. (2000) revealed that chronically applied aqueous NH_4NO_3 reduced the activity of the ligninolytic enzyme produced by white-rot fungi. Frey et al. (2004) reported that active fungal biomass was lower in fertilized plots compared with control plots, resulting in significantly lower fungi/bacteria biomass ratios of in the N-treated plots. The shift in the microbial community composition is accompanied by a significant reduction in the activity of phenol oxidase, a lignin-degrading enzyme produced by the white-rot fungi; this observation indicates that N fertilization may decrease the decomposition of residues, particularly in the late decomposing stages. The reduction in the mineralization of residues in later stages indicates that a greater amount of residue C is sequestered in the soil or incorporated into the microbial biomass (Abro et al. 2011).

5.3 Compacting and irrigation

Intensive mixing of the soil increases the soil-residue contact surface area, enhances microbial colonization, and stimulates maize residue and the decomposition of SOM (Chen et al. 2007). Following intensive mixing by rotary tillage, compacting (0.4 kg cm^{-1}) is needed to improve the seed–soil contact, soil moisture capacity, exchange of water and nutrients, freezing tolerance, and overwintering survival rate of wheat seedlings; these improvements lead to increases in plant development and grain yields (Table 2) (Jia et al. 2010). Compacting decreases the emergence rate of seedlings. This disadvantage could be compensated for by increasing the seeding rate (525 seedlings/m^2) and using relatively shallow sowing (2–3 cm in depth), which can improve stand establishment (Jia et al. 2010).

To some extent, higher soil moisture tends to enhance the decomposition of crop residues, although very high moisture levels may reduce the process (Li et al. 2006b; Abro et al. 2011). Li et al. (2005) revealed that optimized irrigation and fertilization management synergized the beneficial effects of maize residues on wheat growth, grain yield, and NUE. However, the interaction between soil moisture and residue retention is not well understood, and studies investigating this interaction are scarce in China. In practice, irrigation is essential to increasing the soil moisture, the root–soil contact, and the overwintering survival of wheat seedling as the mean air temperature falls to 3 °C in the late fall or early winter.

6 Conclusions

In China, farmers often prefer to burn or remove crop residues. Conventional tillage without residue retention generally decreases soil quality in terms of the microbial community and soil aggregation.

Recently, the residue left behind after the maize harvest using a combine has begun to be incorporated into the soil with conventional tillage. This practice might improve soil quality and influence the growth and development of the wheat crop. Some residue retention practices also produce side effects, including an increased transpiration rate and decreased soil moisture at the early stages of wheat growth, poor crop establishment, and increased freezing stress (Table 3). The latter is caused by shallow sowing and decreased root penetration; the heavy residue on the soil surface may block movement of the planter through the soil (Fig. 5a), or residues buried in the subsoil (Fig. 5b) act as barriers to root growth. Therefore, there is an urgent need to develop new technologies for proper tillage and residue management.

No-till systems with residue retention improve the physical and chemical properties of soil. However, the growth of wheat crops is not consistently correlated with these improved soil regimes. Full maize residues left on the soil surface are too heavy for proper wheat establishment. Thus, no till with a great amount of residue cover is characterized by slowed initial plant growth and, in some cases, increased late plant growth and final grain yield. Moreover, the positive effects are not completely distinct in the short term and may be dependent on the soil type. For instance, in Cumulic Phaeozem or thermic Cumulic Haplustoll soils (Verhulst et al. 2011a) and in sandy soils under rainfed conditions (Wang et al. 2012), no till with residue mulching may be a promising practice. Further studies that explore the advantages of this cropping system and the improvement in wheat productivity should be undertaken. When sustainability and water savings are considered, the maize residues retained on the soil surface in permanent bed planting arrangements appear to be a good option for irrigated wheat-based cropping systems (Verhulst et al. 2011b).

Reduced tillage coupled with residue mulching increases the SOC, soil aggregation, water infiltration rate, and soil water retention while decreasing bulk density near the soil surface. Additionally, the poor stand establishment observed with conventional tillage may be partially overcome by seed strip rotary tillage using a reduced-tillage drill that moves approximately 50 % of the residues to the ridges of planting rows. Thus, the root penetration barrier in the seed strip is largely diminished compared with conventional tillage. The use of residue mulching in conjunction with reduced tillage may be the most promising way to improve the soil quality and sustain/improve crop production in China.

To date, most studies have demonstrated that residue retention improves wheat growth and enhances grain yield in China. These improvements are dependent on the soil quality, including the physical, chemical, and biological properties of soil. However, these studies have not provided enough detailed data

Table 2 Effects of compaction on the agronomical traits of wheat with maize residue incorporation

Treatment	Emergence rate (%)	Winter survival (%)	Spikes per m^2	Grains per spike	1,000-grain weight (g)	Grain yield (g m^{-2})
Compacting (0.4 kg cm^{-1})	74b	81a	708.35a	39.2a	40.3a	951.0a
No compacting	78a	70b	665.00b	34.7b	42.0a	823.9b

This compaction improves the conservation of soil moisture and results in a lower emergence rate but improves seed–soil contact, soil moisture capacity, exchange of water and nutrients, greater winter survival, viable tillers, and better stand establishment; these improvements lead to an increase in grain yields. Means followed by the same letter within a column are not significantly different by a Tukey test ($P<0.05$). Source: Jia et al. (2010)

Table 3 Comparison between conventional and conservation tillage patterns with maize residue retention in maize–wheat double cropping system

Tillage	Advantages	Disadvantages
Conventional	Rapid decomposition of residue; increase the content of SOM, water retention, decrease the soil bulk density and improve the soil texture; increase the C stock and C sequestration; improve the ability of ROS scavenging, promote the photosynthetic rate, plant growth, and delay the plant senescence during grain filling; and beneficial effects can be produced in the first year of residue retention	Lead to shallow sowing and low root penetration; higher occurrence of pathogenic bacteria contained in the maize residue; lower soil moisture and lower soil–seed (seedling) contact at the early stage of wheat growth, resulting in the higher susceptibility of wheat to drought and freezing stresses; and lead to a greater C/N ratio (65–85:1) which is harmful to microbial growth and depresses the residue decomposition
Conservation	Reduce runoff of rainfall and soil erosion and increase water infiltration and conservation, particularly adapted to dry areas and semiarid regions; increase the WUE, SOC content, soil microbial biomass C, aggregate stability, decrease evapotranspiration and soil water depletion, and improve soil conservation and fertility; decrease the subsoil bulk density; protection of the surface layer by residue mulching against the action of falling raindrops; and improve the microenvironments of wheat field (Fig. 4)	Soil organic nutrients remain on the surface and may decrease the wheat productivity in the first several years of residue retention; higher occurrence of pathogenic bacteria contained in the maize residue; and generally, beneficial effects can be produced 2–3 years later

Conservation tillage (zero or reduced tillage with residue retention) shows more beneficial effects and fewer negative effects on soil quality and wheat development compared with conventional tillage (complete tillage with residue retention)

ROS reactive oxygen species, *SOM* soil organic matter, *WUE* water use efficiency

to direct the integrated use of maize residue combined with tillage methods and field management. Due to the diverse of ecology of China, the imbalance in the soil C/N ratio, the possible allelopathy of wheat plants and, in some cases, the increased occurrence of pests and insects, residue retention may cause declines in wheat grain yield and/or quality. Therefore, new techniques should be explored to fully exploit the advantages and eliminate the disadvantages of residue retention. This research requires approaches that systematically seek to explicate the mechanisms by which residue retention promotes wheat productivity. A complete understanding of these underlying mechanisms will enable residues to be scientifically optimized for use in sustainable agricultural systems. More attention should be paid to soil quality; the interactions among soil, plants, and microorganisms; the interactions among tillage, residue management, and crop sequence; the relations between residue decomposition and micro-flora activity; the dynamics and root uptake of soil water and nutrients; the optimal residue retention amount for different agro-ecosystems; and other factors related to wheat growth and yield after long-term residue retention. New techniques requiring study include the cutting of the maize residues, the acceleration of residue decomposition, the improvement of seeding quality, the prevention of plant diseases, and insect pests and the adaptive application of fertilizers.

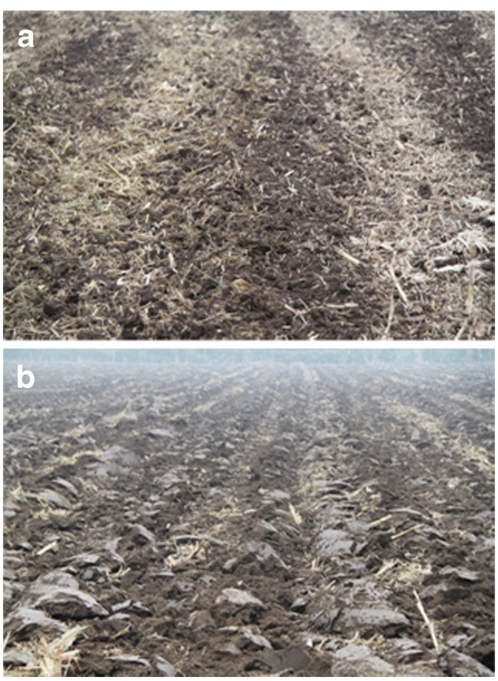

Fig. 5 Tillage with residue retention. **a** The soil is tilled using a rotary tiller, showing the non-uniform distribution of residue. It is difficult to manage further the residues retained on the topsoil, which may severely affect seeding quality and wheat stand establishment. **b** The residues are incorporated by deep plowing but maintained at the subsoil and thus create a barrier that depresses root penetration (photo credit: Jisheng Si)

In summary, residue retention is not a single practice and must be performed with a complete set of techniques, including effective residue cutting, appropriate tillage patterns, correct sowing density and depth, appropriate compacting, and proper compacting tools. The correct selection of these elements would greatly contribute to sustainable agriculture in the target area. At present, reduced tillage combined with residue retention may be the most appropriate practice in most regions of China (Figs. 2, 3, and 4).

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