

## Suppression of weeds and weed seeds in the soil by stubbles and no-tillage in an arid maize-winter wheat-common vetch rotation on the Loess Plateau of China postprint

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### Abstract

Reduced tillage provides ecological and economic benefits to arable land on the Loess Plateau of China, where soil erosion has long been a serious problem and soil water availability is largely restricted. However, high abundances of weeds in reduced tillage systems cause significant yield losses. In this study, we explored the effects of no-tillage and stubble retention on the number and density of weeds and weed seeds in a 12-year maize-winter wheat-common vetch rotation on the Loess Plateau. Four treatments including conventional tillage, no-tillage, conventional tillage+stubble retention and no-tillage+stubble retention were designed and applied. We found that no-tillage increased the number of weed species and weed density in most of the crops, while stubble retention decreased weed density in maize and tended to suppress weeds in both no-tillage treatments (no-tillage and no-tillage+stubble retention). No-tillage led to an increase in the number of weed species in the weed seedbank and tended to increase seed density during the spring growth of winter wheat, but it decreased seed density during post-vetch fallow. Stubble retention tended to reduce seed density during the spring growth of winter wheat and post-vetch fallow. We concluded that no-tillage can promote weeds in the experimental crop rotation, while stubble retention suppresses weeds in untilled fields. The combined effects of stubble retention and no-tillage on weed suppression varied among the three crops. Based on these results, we recommend stubble retention in untilled legume-crop rotations on the Loess Plateau to improve the control of weeds.

## Full Text

### Preamble

#### Suppression of Weeds and Weed Seeds in the Soil by Stubbles and No-Tillage in an Arid Maize-Winter Wheat-Common Vetch Rotation on the Loess Plateau of China

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**Abstract:** Reduced tillage provides ecological and economic benefits to arable land on the Loess Plateau of China, where soil erosion has long been a serious problem and soil water availability is largely restricted. However, high abundances of weeds in reduced tillage systems cause significant yield losses. In this study, we explored the effects of no-tillage and stubble retention on the number and density of weeds and weed seeds in a 12-year maize-winter wheat-common vetch rotation on the Loess Plateau. Four treatments including conventional tillage, no-tillage, conventional tillage+stubble retention and no-tillage+stubble retention were designed and applied. We found that no-tillage increased the number of weed species and weed density in most of the crops, while stubble retention decreased weed density in maize and tended to suppress weeds in both no-tillage treatments (no-tillage and no-tillage+stubble retention). No-tillage led to an increase in the number of weed species in the weed seedbank and tended to increase seed density during the spring growth of winter wheat, but it decreased seed density during post-vetch fallow. Stubble retention tended to reduce seed density during the spring growth of winter wheat and post-vetch fallow. We concluded that no-tillage can promote weeds in the experimental crop rotation, while stubble retention suppresses weeds in untilled fields. The combined effects of stubble retention and no-tillage on weed suppression varied among the three crops. Based on these results, we recommend stubble retention in untilled legume-crop rotations on the Loess Plateau to improve the control of weeds.

**Keywords:** agricultural conservation practice; crop rotation; no-tillage; rainfed soil; soil seedbank; stubble retention; weed control

## 1 Introduction

Soil erosion has long been a serious problem on the Loess Plateau of China, leading to soil deterioration and yield loss in many cropping systems (Chen et al., 2008). Conventional tillage, which is commonly used in cropping systems on the Loess Plateau, has exacerbated soil erosion, and the loss of the productive layer of soil has resulted in depleted levels of soil fertility. Agricultural conservation practices, such as stubble retention and reduced tillage, have been shown to conserve soil fertility by reducing soil erosion (Lafond et al., 2009; Carr et al., 2013; Sommer et al., 2014; Owen et al., 2015). However, some trade-offs of

these conservation practices, including increasing complexity of weed control, have generated concern.

Pernicious arable weeds cause severe economic losses if left uncontrolled or if significant management costs are required (Hamill et al., 2004; Tominaga and Yamasue, 2004). Numerous physical, chemical, and biological weed management strategies have been developed to control or reduce weed pressure on crops (Smith et al., 2010; Worthington and Reberg-Horton, 2013). The traditional practice of frequent tillage effectively reduces weed abundance, and most cropping practices control within-field plant diversity in favor of a single crop species (Legere et al., 2005), but conventional tillage may also lead to soil erosion problems due to continual disturbance and exposure of topsoil to weathering processes. Soil erosion is particularly problematic in dryland areas such as the rainfed Loess Plateau. Although reduced tillage has proven effective in reducing long-term soil erosion and improving soil fertility (Hobbs et al., 2008; Paul et al., 2013; Sommer et al., 2014), it increases the difficulty of weed control, leading to unacceptable yield loss and, consequently, increased reliance on herbicides (Cardina et al., 2002; Hyvönen and Salonen, 2002; Feldman et al., 2010). Due to lower levels of disturbance, no-tillage (or heavily reduced tillage) facilitates the development of larger and more diverse weed seedbanks (Feldman et al., 2010), where the accumulation of seeds in the topsoil (0–5 cm) may result in higher weed incidence (Cardina et al., 2002). However, the shallower distribution of seeds facilitates feeding by rodents and carabids or infection by pathogens (Vander Wall, 1998; Blackshaw et al., 2005; Gallandt et al., 2005; Bohan et al., 2011; Kulkarni et al., 2015), leading to weed reduction.

Other agricultural practices, such as stubble retention and crop rotation, are potentially useful for controlling weeds. For example, weed density and biomass are lower in stubbled land than in bare land (Moore et al., 1994; Reberg-Horton et al., 2012), and stubbles may retard seedling growth, thus reducing seed return to the soil later in the season. Stubble retention maintains seeds at the soil surface and provides habitat for fauna, including beneficial invertebrate predators. Consequently, these weed seeds may be consumed or become infected by pathogens (Vander Wall, 1998; Blackshaw et al., 2005; Gallandt et al., 2005; Bohan et al., 2011; Kulkarni et al., 2015). Furthermore, levels of infection may be enhanced with increased topsoil water content under stubble cover (Chen et al., 2009). Some researchers have shown that compounds such as allelochemicals, released from crop stubbles, may restrict seed germination and seedling growth (Baziramakenga et al., 1995; Belz, 2007; Duke, 2010). However, the effectiveness of stubbles on weed control is largely dependent on stubble density (Moore et al., 1994; Reberg-Horton et al., 2012). The practice of crop rotation has traditionally been used in agriculture, as it affects weeds (Melander et al., 2005; Ryan et al., 2008) and weed seedbanks under conventional tillage (Cardina et al., 2002) that respond to specific crops and associated management practices (Liebman and Dyck, 1993; Lemerle et al., 2001; Teasdale et al., 2004; Melander et al., 2005; Ryan et al., 2008; Andrew et al., 2015; Costanzo and Barberi, 2016).

The adoption of rotations in conjunction with conservation practices, such as reduced tillage and stubble retention, might increase weed species diversity across the rotation (Kegode et al., 1999; Murphy et al., 2006; Nord et al., 2011) and reduce weed abundance. Reduced tillage and stubble retention on the Loess Plateau have proven effective in increasing soil moisture and nutrient availability (Chen et al., 2009). However, weed control problems under these practices have restricted their combined application. Crop rotations that include winter wheat (*Triticum aestivum* L.) and some legume species are widely used in this rainfed area to improve soil fertility through enhanced soil organic matter, nitrogen, and phosphorus content (Liu et al., 2000; Wang et al., 2006; Yang et al., 2011), increased diversity and activity of soil microorganisms (Yang et al., 2013), and improved soil water content (Shen et al., 2009). This rotation type is also important in livestock husbandry for forage provision (Li et al., 2002; Ren, 2002; Zhao et al., 2011). However, the effects of no-tillage and stubble retention on weed and weed seed abundance in these rotations are not well understood.

In this study, we hypothesized that stubble retention in a no-tillage crop rotation system could reduce weed and weed seed abundance. We assessed the effects of tillage, stubble retention, and their combination on weeds and the weed seedbank in each crop of a maize (*Zea mays* L.)-winter wheat-common vetch (*Vicia sativa* L.) rotation on the rainfed Loess Plateau of China.

## 2.1 Study Site

The trial was conducted at the Qingyang Loess Plateau Experimental Station of Lanzhou University (35°40 N, 107°51 E; 1298 m a.s.l.), Gansu Province, China. The long-term average annual precipitation is 543 mm, with nearly 70% of the total falling between July and September. Precipitation from September 2012 to October 2013 (Fig. 1a [Figure 1: see original paper]) was 36% higher than the average. Air temperature from September 2012 to October 2013 was close to the annual average temperature (9.3°C), with the lowest and highest temperatures occurring in December and August, respectively (Fig. 1b). The average frost-free period of 255 days approximates the annual cropping window for this region. Most agricultural sandy-loam (70% silt) soils of this region are Heilu soil types (Shen et al., 2009), classified as Entisols by the USDA (Soil Survey Staff, 1999).

Fig. 1 Monthly precipitation (a), and average maximum air temperature (Tmax) and average minimum air temperature (Tmin; b) from September 2012 to October 2013 at the Qingyang Loess Plateau Experimental Station of Lanzhou University

## 2.2 Experimental Design

We applied four tillage and stubble treatments to crops in a maize (Zhongdan 2)-winter wheat (Xifeng 24)-common vetch (Lanjian 3) rotation from 2001 to 2013. The four treatments comprised tillage (T), tillage+stubble retention (TS), no-tillage (NT), and no-tillage+stubble retention (NTS). Under tillage treatments

(T and TS), soil was tilled twice, immediately after harvest and before sowing; while under no-tillage treatments (NT and NTS), there was no soil disturbance except at sowing with a no-tillage seeder. For stubble treatments (TS and NTS), the previous crop's stubble was returned to or left in the fields. Experimental plots (4 m × 13 m each) were arranged in a randomized block design with three replicates per treatment.

We established two phases in 2001, one starting with maize in April and another with soybean (*Glycine max* (L.) Merr.) in June, to ensure the three crops (maize, winter wheat, and soybean) could be harvested annually (Table 1). In 2011, common vetch replaced soybean in the crop sequence. Agronomic practices such as seeding and fertilization were conducted following provincial standard recommendations (Yang et al., 2013). During 2001–2012, weed control was mainly by hand-cutting. Specific herbicides for controlling broadleaf species were applied to winter wheat at the spring growth stage (Zadoks 30–31) and to maize before seedling emergence (Zadoks 01–03). No herbicides or hand-cutting were applied in 2013.

Table 1 Crop sequences and stubbles in the field under two phases from 2001 to 2013

### 2.3 Measurement of Growing Weeds

The number of weed species and individual counts for each species were recorded in five 0.5 m × 0.5 m quadrats per plot on five occasions for each crop between April and September 2013. Weeds within quadrats were removed and identified at Zadoks stages 13 (13 May), 26 (2 June), 35 (25 June), 61 (18 July), and 73 (10 August) for maize; at Zadoks stages 31 (26 March), 45 (22 April), 61 (13 May), 73 (2 June), and 92 (25 June) for winter wheat; and at sowing (25 June), seedling (17 July), branching (8 August), flowering (2 September), and podding (20 September) stages for common vetch. The total number of species per plot was the sum of all species present across all quadrats, with a species counted once if present at more than one sampling occasion.

### 2.4 Measurement of Weed Seedbank

Soil samples were collected with a drill (5 cm diameter) in March 2013 during post-vetch fallow in Phase 1 and during spring growth of winter wheat (Zadoks 30) in Phase 2 at depths of 0–5, 5–10, 10–20, and 20–30 cm. Samples from five holes per plot were combined into one composite sample. Samples were placed in separate pots in a greenhouse to allow weed seed germination and seedling emergence. Greenhouse temperature was set to 25°C and 18°C for 14 and 10 hours (day and night, respectively), with 40% relative humidity. Emerged seedlings were identified and removed from pots at 7-day intervals starting 15 days after germination until no new seedlings emerged. Weed seedbank species number and density were determined from seedling records.

## 2.5 Statistical Analysis

Effects of crop growth stage, stubble retention, and tillage on weeds and weed seedbank were tested using analysis of variance (ANOVA), with P-values generated using the Holm-Sidak test in SigmaPlot 12.0. Differences among treatments were determined using two-way ANOVA.

### 3.1 Growing Weeds

We recorded 28 weed species from 15 families, among which 14 annuals and 7 perennials occurred at very high frequencies (Table 2 ). The occurrence and characteristics of each weed at different crop phases have been presented in a preliminary report (Zhao et al., 2015).

Crop growth stage and tillage affected weed species number in all three crops, with an interaction between these factors (Table 3 ). Stubble retention affected species number only in maize, where a stubble retention  $\times$  crop growth stage  $\times$  tillage interaction was observed. Weed species number increased initially, then decreased before increasing again from spring growth to harvest in all treatments for winter wheat. Generally, more species were found in NT and NTS treatments than in T and TS treatments (Fig. 2a [Figure 2: see original paper]). During common vetch growth, species number increased after an initial decrease, then continued to decrease in T and TS treatments, but steadily decreased in NT and NTS treatments (Fig. 2b). Species number was higher in NT and NTS treatments than in T and TS treatments before August, but lower thereafter. During the maize growing season, species number initially increased then decreased in all treatments except NTS, where it increased after 18 July (Fig. 2c). Species number in maize was generally higher in NT and NTS treatments than in T and TS treatments, but was lowest in NTS on 18 July. Overall, total weed species number was increased by no-tillage (NT and NTS) in winter wheat and maize, but tended to be reduced by stubble retention (Fig. 2d). Total weed species number in common vetch did not vary among treatments, but was lowest in the NTS treatment.

As shown in Table 3, crop growth stage and tillage affected weed density in all three crops, with a crop growth stage  $\times$  tillage interaction. Stubble retention affected weed density only in maize, where stubble retention  $\times$  crop growth stage and stubble retention  $\times$  tillage interactions were observed. From spring growth until winter wheat harvest, weed density increased then decreased in NT and NTS treatments, whereas it continued increasing through the growing season in T and TS treatments, culminating in a sharp rise (Fig. 3a [Figure 3: see original paper]). Weed density was greater in NT and NTS treatments than in T and TS treatments. In common vetch, a sharp decrease in weed density in all treatments was followed by a gradual, steady decline in NT and NTS treatments, whereas a subsequent increase was followed by a steady decrease in T and TS treatments (Fig. 3b). Weed density was greater in NT and NTS treatments than in T and TS treatments before August, but the reverse was observed thereafter.

For maize, weed density increased then decreased in all treatments except NTS, where it gradually and steadily decreased (Fig. 3c). Weed density was greater in NT and NTS treatments than in T and TS treatments before June. After June, weed density followed the order:  $T > NT > TS > NTS$ . Overall, weed density was increased by no-tillage treatments (NT and NTS) in winter wheat and common vetch, but tended to be reduced by stubble retention (Fig. 3d). Moreover, stubble retention also reduced weed density in maize.

### 3.2 Weed Seedbank

Except for tillage affecting weed species number in the seedbank during winter wheat spring growth, stubble retention or tillage had no effect on species number in other cases (Table 4). Total weed species number in the seedbank was higher during winter wheat spring growth in NT and NTS treatments than in T treatment, while no significant differences existed among NT, TS, and NTS treatments, nor between TS and T treatments (Fig. 4 [Figure 4: see original paper]). Additionally, no significant differences in weed seedbank species number were observed among treatments during post-vetch fallow.

Stubble retention or tillage had no effect on weed seed density in the seedbank during winter wheat spring growth, but these treatments affected seed density during post-vetch fallow (Table 4). During winter wheat spring growth, no differences in soil weed seed density were observed among treatments, but during post-vetch fallow, weed seed density was greatest in T treatment and lowest in NTS treatment (Fig. 5 [Figure 5: see original paper]).

### 4.1 Effect of Crop Growth Stage on Weed Species Number and Weed Density

Weed species number and density varied during the growth period of all three crops (winter wheat, common vetch, and maize), with similar trends observed across almost all treatments (T, NT, TS, and NTS) within each crop. The similarity in weed changes among treatments is largely attributed to shared traits among weeds, as weed growth is closely associated with the crop (Liebman and Dyck, 1993; Lemerle et al., 2001; Teasdale et al., 2004; Melander et al., 2005; Ryan et al., 2008; Andrew et al., 2015; Costanzo and Bàrberi, 2016). We also found minor treatment effects. For example, increases in weed number and density in common vetch after 17 July in T and TS treatments may have resulted from tillage in late June that stimulated seed germination (Legere et al., 2005). Differences in species number and weed density also suggest that exogenous factors associated with tillage and stubble retention may have disturbed natural weed growth, but the impact on weed germination and growth depends on the intensity of these factors (Moore et al., 1994; Cardina et al., 2002; Reberg-Horton et al., 2012). In contrast, weed species number sharply decreased on 18 July in the NTS treatment. We infer this resulted from high germination failure or seedling mortality due to excessive water accumulation (Chen et al., 2009)

that likely occurred following heavy rainfall (224 mm, 30% of the annual total) in early July 2013 at the study site.

## 4.2 Effect of No-Tillage on Weeds and Weed Seedbank

We found that tillage affected weed species number and density in both the weed seedbank and growing weeds. Generally, weed species number and density were greater under no-tillage than under conventional tillage conditions. Lower disturbance levels associated with no-tillage benefit the establishment of larger, more diverse weed seedbanks (Feldman et al., 2010), especially in the top 5 cm of soil (Cardina et al., 2002). Seed accumulation in the soil seedbank may result in large numbers of germinated species later in the season (Cardina et al., 2002), and subsequently, great numbers of seeds return to the soil seedbank. Thus, under no-tillage conditions, weed species richness and diversity are generally higher than under conventional tillage (Hyvönen and Salonen, 2002). In contrast, weed seed density in the seedbank during post-vetch fallow was lower under no-tillage (NT and NTS) and tilled stubble retention (TS) conditions than under conventional tillage. This is possibly due to winter presence of seed predators at the study site (data not shown) consuming seeds distributed in the upper regions of the topsoil (Vander Wall, 1998; Blackshaw et al., 2005; Gallandt et al., 2005; Feldman et al., 2010; Bohan et al., 2011; Kulkarni et al., 2015).

In some circumstances, no-tillage has shown either no or negative impacts on weeds (Cardina et al., 2002). In this study, we recorded complex responses in growing weed number and density to no-tillage conditions in common vetch and maize crops. This variation may be attributed to the combined effects of stubble retention and tillage under crop rotation.

## 4.3 Effect of Stubble Retention on Weeds and Weed Seedbank

Our findings show that stubble retention affected growing weed number and density in maize, where weed density was reduced with common vetch straw retention regardless of tillage conditions. The retained common vetch straw endured for almost a year (from October to September), possibly due to reduced decomposition rates at low winter temperatures (near  $-7^{\circ}\text{C}$  in December 2012 and January 2013). The smothering effect of straw on weed seedling growth therefore reduces seed return later in the season, but straw retention effectiveness depends on the amount of stubble applied (Moore et al., 1994; Reberg-Horton et al., 2012), and some seeds on stubble or soil surface may be consumed by seed predators (Vander Wall, 1998; Blackshaw et al., 2005; Gallandt et al., 2005; Bohan et al., 2011; Kulkarni et al., 2015). In this study, weed seedbank density was low during post-vetch fallow with stubbles. Improved topsoil moisture status under stubble cover (Chen et al., 2009) may have increased pathogen infection risk (Blackshaw et al., 2005; Kulkarni et al., 2015), resulting

in seed viability loss. Additionally, weed growth and seed production may have been suppressed by allelopathic compounds released from decomposing vetch straw (Baziramakenga et al., 1995; Belz, 2007; Duke, 2010). Reduced seed production in post-vetch stubbles inevitably leads to reduced weed density in the subsequent maize crop, highlighting how crop rotations play a critical role in determining weed communities by modulating resource competition (Lemerle et al., 2001; Melander et al., 2005; Ryan et al., 2008; Andrew et al., 2015; Costanzo and Bàrberi, 2016).

In this study, retaining maize or winter wheat stubbles had no effects on weed and seed number and density in winter wheat or common vetch, suggesting either minimal stubble retention effects on weeds or insufficient stubble amounts to elicit changes in weed dynamics (Moore et al., 1994; Reberg-Horton et al., 2012). Improved soil moisture in stubbles (Chen et al., 2009) benefits seed germination, and seed shed prior to and at harvest may be protected from predation and wind dispersal by stubble cover in some seasons. Benefits to weed and seed number and density may partially counteract suppressive effects of stubble retention, making the overall stubble effect appear benign.

#### **4.4 Combined Effects of Stubble Retention and No-Tillage on Weed Occurrence Under Legume-Crop Rotations on the Rainfed Loess Plateau**

The combination of stubble retention with no-tillage had few impacts on weeds in winter wheat and common vetch, but not in maize. The reasons are unclear, but conflicting effects of the two treatments may have led to this overall outcome (Kegode et al., 1999; Murphy et al., 2006; Nord et al., 2011). Furthermore, we noted that dominant weed species accompanying each crop varied among crops (Zhao et al., 2015), which may have influenced allelopathy effectiveness in weed control with stubbles. Although a clear, standard response to stubble retention in untilled fields remains to be confirmed, we recommend that on the rainfed Loess Plateau, stubble retention and no-tillage can be employed to improve weed control in legume-crop rotations.

### **5 Conclusions**

We explored the effects of no-tillage and stubble retention on weeds and weed seedbanks in a 12-year maize-winter wheat-common vetch rotation on the Loess Plateau of China. Results suggested that no-tillage increased weed and weed seed number and density, whereas stubble retention in untilled fields had suppressive effects. Stubble retention combined with no-tillage had crop-specific effects on weed suppression. We recommend applying no-tillage in conjunction with stubble retention in legume-crop rotations in agricultural systems on the Loess Plateau that are subject to soil erosion and exhibit very low soil moisture levels.

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*Note: Figure translations are in progress. See original paper for figures.*

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