Effects of the interaction between temperature and revegetation on the microbial degradation of soil dissolved organic matter (DOM) – A DOM incubation experiment

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ABSTRACT

DOM is the most bioavailable organic pool in the soil. The restoration of vegetation on abandoned cropland has a major impact on the concentration and composition of the DOM and thus affects the biodegradability of the soil DOM. Understanding the response of the microbial degradation of the DOM to temperature is important to maintain soil bioavailable organic matter in the field. We conducted a laboratory DOM solution incubation experiment to examine the temporal dynamics of DOM concentrations at temperatures of 4 °C (low), 20 °C (medium), and 35 °C (high) for four types of land uses: sloped cropland, grassland, shrub land, and woodland. Ultraviolet–visible and fluorescence spectroscopy were used to determine the structural complexity of the DOM. The conversion of the sloped cropland to shrub land and woodland significantly increased contents of DOC, DON, and recalcitrant substances in DOM solution, such as humic-like material and fulvic acid, and stabilised the DOC pool, and reduced the decomposition of the DOC at 20 °C and 35 °C. The conversion of the sloped cropland to woodland dramatically reduced TDN decomposition. The DON loss after 60-day incubation significantly correlated with the initial content of tryptophan-like material. The biodegradability of the DON was higher and more sensitive to temperature than that of the DOC. Rising temperature initially promotes the decomposition of tryptophan-like material, and later promotes the degradation of more recalcitrant substances, such as humic-like material and fulvic acid, which enhanced the decomposition of the DOC and DON. The results suggest that the conversion of sloped cropland to shrubland and woodland not only promoted the accumulation of DOC, TDN, and recalcitrant substances in DOM solution, and decreased their biodegradability but also decreased the temperature sensitivity of the decomposition of the DOC and DON. Therefore, shrubland and woodland were the optimal choices for revegetation in the Loess Plateau of China.

1. Introduction

The DOM represents < 0.25% of the total soil organic matter and facilitates the solubility and mobility of metals and organic compounds (Kalbitz and Knappe, 1997; Temminghoff et al., 1997). The DOM plays an important role in the cycling of carbon and nitrogen and controls the nutrient balance in terrestrial ecosystems (Qualls and Haines, 1992). Approximately 10–88% of the DOM, depending on its source, could be degraded by microorganisms (Kalbitz et al., 2003b; Kalbitz et al., 2000). The decomposition of the DOM is an important process controlling the dynamics of the DOM in the soil, which can alter the dynamics of the turnover and transport of contaminants in soils and their delivery to aquatic ecosystems (Engelhaupt et al., 2003; Findlay et al., 2003) and can regulate the production of greenhouse gases, such as CH4.

Abbreviations: DOM, dissolved organic matter; DOC, dissolved organic carbon; DON, dissolved organic nitrogen; DOP, dissolved organic phosphorus; TDN, total dissolved N; SOM, soil organic matter; SUVA254, UV absorbance at 254 nm; SUVA280, UV absorbance at 280 nm; EEM, excitation-emission matrix; C1, UVA humic-like component that is related to fulvic acid; C2, low-molecular-weight humic material; C3, tryptophan-like material; C4, high-molecular-weight and aromatic humic material

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and N$_2$O, by altering microbial processes (Lu et al., 2000; Yavitt et al., 1997).

The response of the decomposition of the soil organic matter (SOM) to increasing temperature is a critical aspect of ecosystem responses to global change. Numerous studies reported that increasing temperatures accelerate the microbial decomposition rate of SOM (Conant et al., 2011; Karhu et al., 2014; von Luetzow and Koegel-Knabner, 2009). One of the primary reasons for this phenomenon is that increased temperatures significantly promote enzyme-mediated reactions, since the SOM is vulnerable to degradation by extracellular enzymes that are produced by soil microorganisms (Davidson et al., 2006; Lawrence et al., 2009; Wallenstein et al., 2009). Microorganisms can only assimilate soluble, low-molecular-weight compounds, and extracellular enzymes produce DOM that is rapidly incorporated by microbes by degrading the SOM through hydrolytic or oxidative processes (Conant et al., 2011). Temperature directly and indirectly regulates the production of the DOM by affecting the biological activities and physico-chemical processes that are the key factors affecting the loss of soil C (Stutter et al., 2007; Sun et al., 2013b). Previous research reported that in bog and forested wetlands, the soil biodegradable DOC peaked during the spring and was the lowest during the summer (Fellman et al., 2008; Fellman et al., 2009). Thus, the mechanism of how temperature regulates the decomposition of DOM helps to explain the impacts of increasing temperatures on the decomposition of the SOM and forecasts of seasonal changes in soil C loss. A previous study conducted in subtropical rivers suggested that biodegradable DOC increased with elevating temperature, and DOC quality is a powerful predictor of temperature sensitivity of biodegradable DOC (Mao and Li, 2018), as decomposition of recalcitrant organic carbon (OC) fraction is generally more sensitive to temperature than labile OC fraction (Shah et al., 2017; Sihai et al., 2016). However, the response of decomposition of the DOM in soil to rising temperature is still not clearly understood (Wang et al., 2014a). Although Wang et al. (2014a) observed that the biodegradability of DOM decreased in response to 4.5 years of warming, the soil incubation method used to investigate the biodegradability of DOM was flawed, since the dynamics of the concentration of the DOM during soil incubation is the net result of the DOM decomposition and the hydrolytic and oxidative degradation of the SOM, as well as the soil’s physical and chemical adsorption and release (Fang et al., 2014). The standard method to analyse the biodegradability of the DOM is to monitor the loss of nutrients in the DOM solution by incubating the extracted DOM (Kalbitz et al., 2003a; Marschner and Kalbitz, 2003; McDowell et al., 2006).

The concentrations and qualities of DOM were largely affected by revegetation (Li et al., 2018; Xiao et al., 2017). The concentrations of the DOM were the highest in forest followed by grassland, and the lowest concentrations were identified in agricultural soils (Huang et al., 2015; Sun et al., 2013b; Xiao et al., 2017). Grassland soils contain relatively higher tryptophan-like compounds and low molecular weight organic acids, than do forest soils, while the DOM from forest has higher humic-like compounds than do those from grassland (Huang et al., 2015; Kov et al., 2018). Additionally, DOC with similar aromatic properties was observed from the cropland, grassland and forest from two research locations in China and Canada (Sun et al., 2013a). Revegetation can greatly alter the microbial composition and vegetation cover that further affects the concentration and composition of the DOM, thereby affecting its biodegradation (Autoio et al., 2016; Kalbitz et al., 2003a). Previous studies observed that forest soils have less biodegradable DOM than agricultural soils, and the amount varies depending on the species of the trees (Kikkila et al., 2006; Sun et al., 2013a). Generally, much is still unknown regarding how vegetation restoration impacts the decomposition of the DOM by altering its chemical composition and structural characteristics. In this study, fluorescence spectroscopy that is a highly sensitive tool and enables the identification of different compounds belonging to specific regions was applied to investigate the composition of the DOM after vegetation restoration.

The Loess Plateau in China covers approximately 62.4 × 104 km$^2$, has a typical semiarid climate, and is known for its long agricultural history and major problems with soil erosion (Wang et al., 2011). The Chinese government implemented the Grain-for-Green project in 1999 to control soil erosion and restore the ecosystem, converting cropland to grassland and woodland (Zhang et al., 2011). Numerous studies have indicated that vegetation restoration in the Loess Plateau has substantially reduced soil erosion and increased the soil’s organic C and N contents, the accumulation of soil DOC and DON, and the microbial abundance and diversity in the soil (Deng et al., 2016a; Ren et al., 2016a; Xue et al., 2013; Zhang et al., 2013b). However, little information is available on how vegetation restoration influences the decomposition of DOM at different temperatures, since temperature and land-use type are the dominant factors affecting the decomposition of soil C (Sun et al., 2013b). Additionally, the DOC and DON are concentrated in the hydrophobic and hydrophilic fractions of the DOM, respectively (Kaiser and Zech, 2000). The hydrophilic fraction has been reported to degrade the most readily (Kalbitz et al., 2003b), so that the biodegradability of the DOC and DON differ (Schmidt et al., 2011). Studies of the biodegradability of the DOM have focused more on the dynamics of the DOC than those of the DON (Cleveland et al., 2004; Ghani et al., 2013; Schmidt et al., 2011). To improve the understanding of DOM decomposition in response to vegetation restoration and temperature, we examined the chemical quality of DOM and the dynamics of the microbial degradation of DOC and DON from sloped cropland, grassland, shrub land, and woodland in the Loess Plateau at three levels of temperature. We hypothesised that (1) revegetation will increase recalcitrant substances in the DOM that decrease its biodegradability, (2) the suitable temperature for microbial degradation of the DOC and DON will vary from soil under different types of vegetation growth that is related to the chemical quality of the DOM, and (3) the dynamics of DOC and DON biodegradation will be differentially affected by temperature.

2. Methods and materials

2.1. Study site and soil sampling

Study sites were established in the Zhifanggou Watershed in Shannxi Province, China (36°44′N, 109°15′E). This small watershed that covers a total area of 8.73 km$^2$ contains landforms and vegetation types typical of the hilly-gully region of the Loess Plateau. The watershed has also been used to monitor vegetation restoration as a field experimental base of the Institute of Soil and Water Conservation, Chinese Academy of Sciences. This study area has a semi-arid climate, a mean annual temperature of 8.8°C, and a mean annual precipitation of 510 mm, mostly from July to September. The soil is mainly comprised of Huangmian soil (calcic cambisols, FAO), developed on wind-deposited loessial parental material and characterised by the parental material, the absence of bedding, a loose silty texture, macroporosity, and wetness-induced collapsibility. The soil pH ranged from 8.3 to 8.9.

The natural ecological environment was severely destroyed by illegal human activities in the middle of the 20th century. All of the croplands with slopes > 15° were converted to grassland and forest when the regulations for converting croplands were implemented in 1999. The conversion has altered the vegetation substantially. The development of grassland (Artemisia sacrorum) Ledeb, shrubland (Caragana korshinskii), and woodland (Robinia pseudacacia) markedly improved the storage of the soil organic C and total N in this area (Zhang et al., 2011).

We chose four sites representing the four types of land uses in June 2015 to investigate the biodegradability of soil DOM: sloped cropland (Setaria italica), grassland (A. sacrorum), shrubland (C. korshinskii), and woodland (R. pseudacacia). These sites had similar elevations, gradients, and slopes and had previously been farmed in similar manners.
All of the soils had developed from the same parental materials. Detailed information for the study sites is shown in Table S1 and S2. Three 20 × 20 m plots were established at least 25 m apart for each type of land use. Soil samples were collected from the top 20 cm using a stainless steel corer 5 cm in diameter after the litter horizons had been removed. All of the sampling points were free of lichens, biological crusts, and any other vegetation within 0.75 m. Twenty soil cores were collected from each plot along an S-shaped pattern and subsequently mixed to form one sample. A total of 12 samples (4 sites × 3 replicate plots per site) were collected. Visible plant roots, stones, litter, and debris were removed from each sample that was later divided into two subsamples. One subsample was stored at 4 °C for use in an incubation experiment, and the other subsample was air-dried for physicochemical analysis. Litter samples were also collected and oven-dried for lignin and cellulose analysis.

2.2. Preparation of DOM solutions and inoculation

A DOM solution was prepared for each sample as described by Kalbitz et al. (2003a, 2003b) by adding distilled water to fresh soil equivalent to 1.5 kg dry soil (1:3 dry soil:water, w/w). All of the extracts were centrifuged at 3000 × g for 10 min and filtered through preswashed cellulose acetate filters (0.45 μm pore size). All of the soil samples were used to prepare inocula. The samples were rewetted to field capacity and incubated for 2 weeks at 20 °C to reactivate the microorganisms. Fifty grams of each soil sample was also shaken with 100 mL of 4 mM CaCl₂ for 30 min followed by filtration through 5 μm filters. The total cell number in the solutions was counted (Kalbitz et al., 2003a) to ensure that the inocula were comprised of numerous microorganisms. The inocula were then added to the respective DOM solutions at a ratio of 1:100 (Kalbitz et al., 2003a, 2003b).

2.3. Incubation experiments

All of the samples were incubated in closed 2-L glass bottles in the dark in incubators at 4 °C, 20 °C and 35 °C for 60 days. Temperature is known to stimulate microbial activity within the physiological range of 0 °C–35 °C (Paul and Clark, 1996). Four degrees Celsius and 30 °C are extremely cold and hot, respectively, for the decomposition of DOM. Twenty degrees Celsius is considered to be a suitable temperature for the decomposition of DOM (McDowell et al., 2006). The solutions were gently shaken by hand each day for 2 min to mix the samples. The incubation bottles were opened twice a week to aerate the DOM solutions for 10 min. Subsamples were taken after 0, 1, 3, 5, 10, 14, 21, 28, 35, and 60 days. The subsamples were filtered through 0.45 μm cellulose acetate membranes to remove both particulate matter and microorganisms. The subsamples were frozen prior to laboratory analysis. A total of 396 subsamples were collected.

2.4. Sample analysis

The contents of TDN, DOC, N-NH₄⁺, and N-NO₃⁻ were measured in all of the subsamples. The DOC contents were determined using a TOC analyser (Liqui TOC II, Elementar, Germany). The TDN contents were determined by utilising an alkaline digestion/ultraviolet (UV) spectrophotometric method (Doyle et al., 2004). The N-NH₄⁺ content was measured by an AA3 continuous-flow autoanalyzer (AutoAnalyzer3-aa3, Bran + Luebbe, Germany). The N-NO₃⁻ content was determined by UV spectrophotometry at 220 and 275 nm (UV2300, Tianmei, Shanghai, China). The DON content was calculated as TDN - (N-NH₄⁺ + N-NO₃⁻). Total soluble polyphenolics were analysed by the Folin-Denis method (Anderson and Ingram, 1994). The contents of cellulose and acid insoluble lignin in litter samples were determined following the procedures of NREL-LAP (Sluiter et al., 2008). The UV–visible absorption at 200–600 nm (1 nm steps) was measured in a 10-mm quartz cuvette with Milli-Q water used as a blank. The specific UV absorbances at 254 and 280 nm were measured for all of the samples. Excitation-emission matrix (EEM) spectrograms of the subsamples for days 0, 1, 3, 5, 10, 21, 35, 60 were measured using an F-4600 fluorescence spectrometer (HITACHI, Japan). The voltage of the photomultiplier tubes was set at 700 V, and the slits for both excitation and emission were 5 nm at a scanning speed of 1200 nm min⁻¹. The EEMs were recorded in a range of excitation wavelengths of 200–450 nm and a range of emission wavelengths of 250–450 nm. The wavelength-dependent intensity of the light source and the light sensitivity of the detector were corrected before measurement. Correction factors supplied by the manufacturer were used to correct the excitation and emission intensities for instrument-specific biases.

2.5. Parallel factor (PARAFAC) analysis

Each EEM was corrected for inner filtering effects by multiplying by a correction matrix that was calculated for each wavelength pair from the sample absorbance by assuming Ex and Em pathlengths of 0.5 cm in a 1-cm cuvette (Ohno, 2002). The data from the same land use type was combined to avoid admixing by the various sources or environmental samples. The EEM spectrogram data was combined into four 3-dimensional arrays that contained 66 samples × 51 excitations × 41 emissions. The Raman scatter effects were removed from the data set before analysis by subtracting the spectrogram for Milli-Q water from the sample spectrogram. Rayleigh scatter effects were removed from the data set by excluding emission measurements at wavelengths less than or equal to the excitation wavelength + 20 nm. Excitation wavelength < 220 nm were removed from the model, because wavelengths < 220 nm are usually associated with high levels of noise and do not contribute relevant fluorescence information (Stedmon et al., 2003; Yamashita and Tanoue, 2003).

Fig. S1 shows the fluorescent components and the proportional distribution of the components of the soil DOM for the four land-use types. The Ex/Em wavelength pairs of component 1 (C1) were centred at 255/440 nm (Fig. S1). This component was identified as a UVA humic-like component that is related to fulvic acid (Cory and McKnight, 2005; Stedmon and Markager, 2005). Component 2 (C2) was centred at excitation/emission (Ex/Em) wavelengths pairs 225/420 nm. This component was associated with low-molecular-weight material and biological activity (Cory and McKnight, 2005; Murphy et al., 2006; Stedmon and Markager, 2005; Stedmon et al., 2003). Two humic-like fluorescent peaks were observed for component 3 (C3) that were centred at excitation/emission (Ex/Em) wavelength pairs 235/360 and 280/360 nm. This component was associated with tryptophan-like material (Cory and McKnight, 2005; Murphy et al., 2006; Stedmon and Markager, 2005; Stedmon et al., 2003). The humic-like fluorescent peak that was centred at the Ex/Em wavelength pair 225/450 nm was identified from component 4 (C4). This component was associated with high-molecular-weight and aromatic humic material (Cory and McKnight, 2005; Stedmon and Markager, 2005; Stedmon et al., 2003).

2.6. Data analysis

A double-fitted exponential curve was applied using the least-square optimisation method on all time series of the loss of the DOC, assuming that the total DOC was comprised of one labile and one stable DOC pool (Kalbitz et al., 2003b). This statistical analysis was performed utilising 1stOpt (7D-Soft High Technology Inc., Beijing, China).

The specific UV absorbances at 254 and 280 nm were measured for all of the samples. Excitation-emission matrix (EEM) spectrograms of the subsamples for days 0, 1, 3, 5, 10, 21, 35, 60 were measured using an F-4600 fluorescence spectrometer (HITACHI, Japan). The voltage of the photomultiplier tubes was set at 700 V, and the slits for both excitation and emission were 5 nm at a scanning speed of 1200 nm min⁻¹. The EEMs were recorded in a range of excitation wavelengths of 200–450 nm and a range of emission wavelengths of 250–450 nm. The wavelength-dependent intensity of the light source and the light sensitivity of the detector were corrected before measurement. Correction factors supplied by the manufacturer were used to correct the excitation and emission intensities for instrument-specific biases.
rate constraints (half-life = ln(2) × k −1). The fits were assumed to be valid when α, k1, and k2 were all > 0 and were rejected if not.

Land-use type, temperature, incubation time, and their interactive effects on DOC, TDN, DON, NO3 −, NH4 +, DOC:DON, SUVA254, SUVA280 and the four identified PARAFAC components were tested using a three-way analysis of variance (ANOVA). Regression analyses were used to test the relationships between the dynamics of DOC and TDN at 4 °C, 20 °C, and 35 °C. A Pearson linear-correlation analysis was used to evaluate the relationship between the loss of DOC, DON, and TDN, DOC: DON, and the initial chemical characteristics of the DOM including the SUVA254, SUVA280, and the four identified PARAFAC components. All of the statistical analyses utilized SPSS 21.0. The figures were graphed utilizing SigmaPlot 10.0. MATLAB 2010a (MathWorks Inc., USA) was used to analyse the EEM data. The PARAFAC modelling of the fluorescence EEMs was conducted with MATLAB using the DOMFluor toolbox (Stedmon and Bro, 2008) following the procedures described by Stedmon and Bro (2008).

3. Results

3.1. Incubation DOC losses and the dynamics of DOC biodegradation

The dynamics of the biodegradation of the DOC were significantly affected by land-use type and temperature during the incubation (Table S3). The initial DOC contents for the four land-use types decreased in the order of shrub land, woodland, sloped cropland, and grassland (Fig. 1). The DOC losses during the 60-day incubation period varied among the three incubation temperatures and the four land-use types. The biodegradability of the DOC was the most sensitive to the incubation temperature in the sloped-cropland and grassland samples and was not significantly influenced in the woodland and shrubland samples (Table 1). The DOC biodegradation during the 60-day incubation period in the sloped-cropland and grassland samples was the highest at 35 °C with 39.7% and 28.9%, respectively, and was the lowest at 4 °C with 18.2% and 15.9%, respectively. The biodegradation at 35 °C and 20 °C was the highest for the sloped cropland and did not differ significantly between the grassland, woodland, and shrubland. The biodegradation of the DOC at 4 °C was the highest for the shrubland and the lowest for the grassland.

The rate of the biodegradation of the DOC was the highest during the first day, and it subsequently decreased rapidly during days 1 to 7. Next, this rate remained near zero until day 60 (Fig. 1). The initial rate for all four of the land-use types increased with incubation temperature. The dynamics of the DOC loss in most of the samples was well fitted by a double exponential model (Table 2). The calculated labile pool varied between 30.4% and 55.7% and was the highest for the sloped cropland and the lowest for the shrubland. The half-lives of the stable pool that were significantly affected by temperature varied between 7 d and 288 d. In contrast, the half-lives of the labile pool that were relatively insensitive to temperature varied between 1.5 d and 5.7 d. The half-lives of the stable pool in the grassland and woodland samples were the lowest at 20 °C. However, the half-life of the shrub land samples was the highest at 20 °C and the lowest at 4 °C, while it was the highest at 35 °C and the lowest at 4 °C in the sloped cropland samples.

3.2. Incubation TDN and DON losses and the dynamics of TDN, DON, NO3 −, and NH4 +

The dynamics of the biodegradation of the TDN and DON were dramatically affected by land-use type but not by the temperature or the interaction between land-use type and temperature (Table S3). The initial TDN and DON contents for the four land-use types decreased in the following order: woodland, shrubland, sloped cropland, and grassland (Fig. 2). The TDN losses during the 60-day incubation period were not significantly affected by temperature for any of the four land-use types (Table 1). The TDN losses were the highest for the grassland, varying from 54.3% to 45.6%, and were the lowest for the shrubland, varying from 17.4% to 8.6%. The DON losses during the 60-day incubation period were the lowest at 4 °C for all four of the land-use types. The DON losses were the highest at 35 °C for the sloped cropland and woodland, while they were the highest at 20 °C for the grassland and shrub land. The DON losses were the lowest for the sloped cropland and varied from 5.8% to 22.8%. The rate of the biodegradation of the TDN, as with that of the biodegradation of the DOC, was the highest during the first day, subsequently decreased rapidly during days 1 to 7, and then remained near zero until day 60 (Fig. 2).

The dynamics of the NO3 − concentration were significantly affected by land-use type, but the dynamics of NH4 + concentration were not (Table S3). The NO3 − content during the 60-day incubation period was the highest for the woodland followed by the shrubland, sloped cropland, and grassland (Fig. 3). The NO3 − contents for the sloped cropland, shrubland, and woodland decreased early during the incubations. The NO3 − content had decreased by the end of the 60-day incubation period for the sloped cropland but increased for the woodland. The NO3 − contents for the grassland and woodland remained stable throughout the 60-day incubation period. The NH4 + contents for all four land-use types decreased early during the incubation period and then increased. The NH4 + contents increased significantly with temperature for all four of the land-use types (Table S3).

3.3. Changes in DOM composition during incubation

The parameter SUVA 254 is associated with the total content of natural organic matter in natural waters (Najm et al., 1994). The parameter SUVA 250 (UV absorbance at 250 nm) was introduced to represent total aromaticity (Sarathy and Mohseni, 2007). Land-use type had a significant effect on the dynamics of SUVA254 and SUVA280 (Table S3). The SUVA254 and SUVA280 were significantly higher for the shrubland and woodland than for the sloped cropland and grassland (Fig. 4). Temperature, however, did not dramatically affect the dynamics of the SUVA254 or SUVA280. Land-use type, temperature, and the interaction of land-use type and temperature had significant effects on the content of C1 (Table S3) that was significantly higher for the shrubland and woodland than the grassland and sloped cropland (Fig. 5). The contents of C2, C3, and C4 were dramatically affected by land-use type (Table S3). The contents of C2 were significantly higher for the grassland and shrubland than for the sloped cropland and woodland (Fig. 5). Incubation time had a significant effect on the contents of C2 for all four types of land-use. The C2 contents for the sloped cropland, grassland, shrubland, and woodland increased within the first three days (Fig. 5) but later decreased between days 10 and 60. The contents of C1 and C2 in all four land-use types at day 60 were lower at 35 °C than at 20 °C and 4 °C. However, this difference was not statistically significant. The content of C3 was significantly higher for the shrubland than the grassland, woodland, and sloped cropland. The incubation time, temperature, and the interaction between the incubation time and temperature significantly influenced the contents of C3 for all four land-use types (Table S3). The contents of C3 decreased slightly within the first day for all land-use types, and then increased before finally decreasing through the end of the experiment (Fig. 5). At day 20, the content of C3 was the lowest at 20 °C and highest at 4 °C, indicating that warming primarily resulted in the decomposition of C3. The content of the C4 was significantly higher for the grassland than the sloped cropland, shrub land, and woodland. Incubation time, temperature, and the interaction between incubation time and temperature also significantly influenced the contents of C4. The contents of C4 first increased early for all of the land-use types before decreasing. The contents of C4 decreased with rising temperature in the grassland, shrubland and woodland, while it was the lowest at 20 °C in the sloped cropland.
3.4. Relationships between DOM composition and DOC, TDN, and DON losses

Differential DOM composition might play a vital role in the biodegradation of the DOC and DON at different incubation temperatures. The DON losses correlated negatively with total soluble polyphenolics, and the TDN losses correlated negatively with acid insoluble lignin (Table 3). At 35°C, the DOC losses correlated negatively with C1, SUVA254, and SUVA280 ($P < 0.01$), The TDN losses correlated positively with C2 and C4 ($P < 0.01$), and the DON losses correlated positively with C3 ($P < 0.01$). At 20°C, the DOC losses correlated negatively with those of the DON, C2, C4, and DOC:DON ($P < 0.01$). The
Table 1
DCO and DOC biodegradation in different land use types and at different temperature.

<table>
<thead>
<tr>
<th>DOM solution</th>
<th>DOC biodegradation (%)</th>
<th>TN biodegradation (%)</th>
<th>DON biodegradation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at 35 °C</td>
<td>at 20 °C</td>
<td>at 4 °C</td>
</tr>
<tr>
<td>Sloped cropland</td>
<td>0.397 ± 0.036a</td>
<td>0.276 ± 0.067b</td>
<td>0.228 ± 0.026e</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.289 ± 0.039b</td>
<td>0.543 ± 0.106a</td>
<td>0.711 ± 0.038ab</td>
</tr>
<tr>
<td>Shrubland</td>
<td>0.299 ± 0.093bc</td>
<td>0.291 ± 0.073b</td>
<td>0.602 ± 0.042c</td>
</tr>
<tr>
<td>woodland</td>
<td>0.252 ± 0.065bc</td>
<td>0.174 ± 0.107bc</td>
<td>0.713 ± 0.064ab</td>
</tr>
<tr>
<td>Sloped cropland</td>
<td>0.326 ± 0.015b</td>
<td>0.350 ± 0.099ab</td>
<td>0.161 ± 0.057e</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.227 ± 0.013c</td>
<td>0.456 ± 0.128ab</td>
<td>0.794 ± 0.061a</td>
</tr>
<tr>
<td>Shrubland</td>
<td>0.270 ± 0.089bc</td>
<td>0.303 ± 0.066b</td>
<td>0.684 ± 0.031b</td>
</tr>
<tr>
<td>woodland</td>
<td>0.221 ± 0.055ed</td>
<td>0.132 ± 0.035c</td>
<td>0.642 ± 0.045bc</td>
</tr>
<tr>
<td>Sloped cropland</td>
<td>0.182 ± 0.032cd</td>
<td>0.265 ± 0.050b</td>
<td>0.058 ± 0.019f</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.159 ± 0.021d</td>
<td>0.468 ± 0.118ab</td>
<td>0.427 ± 0.050d</td>
</tr>
<tr>
<td>Shrubland</td>
<td>0.235 ± 0.090bc</td>
<td>0.293 ± 0.109b</td>
<td>0.509 ± 0.048d</td>
</tr>
<tr>
<td>woodland</td>
<td>0.193 ± 0.069ed</td>
<td>0.086 ± 0.055c</td>
<td>0.619 ± 0.032c</td>
</tr>
</tbody>
</table>

Different letters in the same column indicate significant differences among different treatments in the same column (P < 0.05).

Table 2
Quantitative measures of the biodegradation of DOM after 60 days incubation: sizes of the labile and stable DOC pools, mineralization rate constants and half-life for the labile (k1) and the stable (k2) DOC pools (samples represent the means of three replicates).

<table>
<thead>
<tr>
<th>DOM solution</th>
<th>Labile DOC (a) (%)</th>
<th>Stable DOC (b) (%)</th>
<th>K1 (day−1)</th>
<th>K2 (day−1)</th>
<th>Half-life 1 (c) (day)</th>
<th>Half-life 2 (d) (day)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at 35 °C</td>
<td>at 20 °C</td>
<td>at 4 °C</td>
<td></td>
<td></td>
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<tr>
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<td>55.7</td>
<td>44.3</td>
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<td>0.0944</td>
<td>1.55</td>
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<td>0.97</td>
</tr>
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<td>57.8</td>
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<td>120.48</td>
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<td>Woodland</td>
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<td>0.2997</td>
<td>0.0078</td>
<td>2.31</td>
<td>88.70</td>
<td>0.95</td>
</tr>
</tbody>
</table>

R²: coefficient of determination of the double exponential model.
- a: rapidly mineralizable DOC; calculated using a double exponential model.
- b: slowly mineralizable DOC; calculated using a double exponential model.
- c: mineralization rate constant of the labile DOC pool (double exponential model).
- d: mineralization rate constant of the stable DOC pool (double exponential model).
- e: half-life of the labile DOC pool.
- f: half-life of the stable DOC pool.

4. Discussion
4.1. Effects of revegetation on chemical quality and microbial degradation of soil DOM

The initial contents of the DOM, DON, NO₃⁻, and TDN were higher for the shrubland and woodland than for the sloped cropland. This finding was consistent with previous research (Xue et al., 2013; Zhu et al., 2014) and indicated that the conversion of the sloped cropland to shrubland and woodland could increase the amounts of labile C and N in the topsoil. The initial DOC, DON, NO₃⁻ and TDN contents, however, were higher for the sloped cropland than the grassland, possibly due to the application of manure, N, and P fertiliser in the sloped cropland (Liang et al., 2012). The SUVA254 and SUVA280 that indicate the aromaticity and average molecular weight compounds in the DOM solution were significantly lower for the sloped cropland and grassland than for the shrubland and woodland. The C1 content that is associated with fulvic acid was also lower for the sloped cropland and grassland than for the shrubland and woodland (Fig. 5). These results imply that the DOM becomes more recalcitrant after revegetation. Previous studies have suggested that the DOM in the topsoil is comprised primarily of recent photosynthetic products, thereby supporting the assumption that the DOM is produced during the decomposition of litter (Froberg et al., 2009; Kaiser and Kalbitz, 2012; Sanderman et al., 2008). The DOM in the topsoil thus has a vegetation-type signature with lignin-derived
phenols and plant-derived carbohydrates dominating (Kaiser et al., 2004; Kaiser and Kalbitz, 2012). The DOM in the topsoil of the sloped cropland mainly originates from manure or inorganic fertiliser and is highly available to soil microorganisms (Singh et al., 2014). Perennial grasses supply C-rich leaf litter, and evergreen shrubs usually produce N-rich leaf litter with high concentrations of secondary compounds such as lignin and phenolics (Bertiller et al., 2005; Carrera et al., 2008; Carrera et al., 2000). In this study, higher contents of soil total soluble polyphenolics, litter cellulose and acid insoluble lignin were observed in shrubland and woodland relative to grassland (Table S3). Previous study suggested that the lignin content of the surface litter is higher in the shrubland than the grassland which would contribute to the higher recalcitrance of the organic matter in the shrubland (Filley et al., 2008). The conversion of farmland into forests also increases the rates of primary production by increasing the inputs from the surface litter and roots (Deng et al., 2016b; Ren et al., 2016b; Wang et al., 2014b). The concentrations of tannin and lignin are higher in the forest than in the grassland and shrub/grassland litter, and more recalcitrant compounds are produced in forests (Zhang et al., 2013c).

The 60-day biodegradation of the DOC was reduced, especially at 35 °C and 20 °C, after the revegetation that facilitated the accumulation of labile C in the topsoil. A previous study also reported that the biodegradable fraction of DOM was lower in forest than in agricultural soils (Sun et al., 2013a). DOC characteristics such as molecular size, chemical structure, and spectroscopic properties are some of the most important factors influencing the biodegradability of dissolved organic matter (Kalbitz et al., 2003a). Aromatic compounds were regarded as recalcitrant and difficult to decompose and these compounds and biodegradability were negatively correlated (Marschner and Kalbitz, 2003; Olefeldt et al., 2013; Sun et al., 2013a), which is in line with our results (Table 2). In this study, the stabilised DOC pool and more recalcitrant DOM after the revegetation are the main factors leading to decreased biodegradability of DOC. The conversion of sloped cropland to woodland dramatically decreased the biodegradation of TDN, but the conversion to grassland promoted this process. The primary reason for this is that the NO₃⁻ content significantly increased in the woodland after the 60-day incubation, and lower initial DOC:DON for the sloped cropland and woodland than for the grassland and shrubland (Fig. S2) would limit the microbial use efficiency of the DON. The contents of the NO₃⁻ for the sloped cropland, shrubland and woodland decreased
significantly within the first day which is in contrast to those from a previous study (Ghani et al., 2013) that reported no significant change in the concentration of NO$_3^-$

This discrepancy was probably due mainly to the high initial contents of inorganic N in the sloped cropland, shrubland, and woodland probably stimulating the activity of autotrophs that use inorganic N as an amino acid N source, thereby contributing to the decrease in NO$_3^-$ contents within the first day. In addition, the high content of litter acid insoluble lignin in shrubland and woodland decreased the biodegradability of TDN, as TDN biodegradation was negatively correlated with litter acid insoluble lignin content (Table 3).

The biodegradation of the DON increased significantly after the sloped cropland converted to grassland, shrubland, and woodland. The biodegradation of the DON correlated significantly with the initial C3 content that has been associated with tryptophan-like material (Cory and McKnight, 2005; Murphy et al., 2006; Stedmon and Markager, 2005). Tyrosine-like fluorescence indicates more highly degraded peptides, and tryptophan-like fluorescence may indicate the presence of intact proteins or less degraded peptides (Yamashita and Tanoue, 2003; Yamashita and Tanoue, 2004). Protein-like fluorescence, the sum of tyrosine and tryptophan-like components, is a useful indicator of biodegradable DOC (Fellman et al., 2008).

Thus, our study suggests that tryptophan-like fluorescence is also a useful indicator of biodegradable DON. The revegetation significantly increased contents of tryptophan-like components leading to the increased amount of biodegradable DON. Revegetation can significantly increase the abundance of soil microbial diversity and microbial activity (Ren et al., 2016a; Zhang et al., 2013a; Zhang et al., 2015) that may have contributed to the enhanced levels of DON biodegradation during the 60-day incubation period after revegetation. In addition, the biodegradability of DON after revegetation was significantly higher than that of the DOC. The DOC and DON tend to concentrate in different DOM fractions – hydrophobic and hydrophilic, respectively (Kaiser and Zech, 2000; Petrone et al., 2009). Hydrophilic components that include carbohydrates generally degrade more rapidly than components that are hydrophobic (Kalbitz et al., 2003b), so the DON is more labile than the DOC. The low biodegradation of the DON in the sloped cropland was probably limited by the low initial content of the DOC, because the biodegradation of the DON was driven by the C demands of microorganisms, rather than by the availability of N (Schmidt et al., 2011).

4.2. Effects of temperature on soil DOM biodegradation

A large proportion of the DOM in soil is humic acid and fulvic acid,
and these humic substances are considered recalcitrant but can at least be partially decomposed by microorganisms (Kisand et al., 2008; Rocker et al., 2012) and are the major constituents of soil organic matter (Hayes and Clapp, 2001). Humic acids with a high molecular weight are more readily degradable than fulvic acid that has a lower molecular weight (Kisand et al., 2008; Rocker et al., 2012). In this study, rising temperature primarily promotes the decomposition of tryptophan-like material, but it only slightly stimulated the decomposition of C3 at the end of the incubation. Rising temperature finally promotes the degradation of more recalcitrant substances, such as humic-like material and fulvic acid, as the contents of C1 and C2 at day 60 for all four land-use types were lower at 35 °C than at 20 °C and 4 °C. The correlation analysis also confirmed that the soil microbes preferred to use different components of the DOM solution at different temperatures. The DOC loss after 60-day incubation at 35 °C was negatively correlated with SUVA254, SUVA280 and the content of C1 that is related to fulvic acid (Stedmon and Markager, 2005), indicating that the biodegradation of DOC at 35 °C was limited by fulvic acid and aromatic compounds. The DOC loss after 60-day incubation at 20 and 4 °C was negatively correlated with the contents of C2 and C4 that are related to low- and high-molecular-weight humic materials. This result implied that the biodegradation of DOC at 20 and 4 °C was mainly limited low- and high-molecular-weight humic materials. In addition, the DOC loss at 4 °C was positively correlated with UVA254, SUVA280 and the content of C1, but no significant correlations were observed between DOC loss at 20 °C and these indexes, indicating that more contents of fulvic acid and aromatic compounds were decomposed at 20 °C relative to 4 °C. These results thus suggested that rising temperature increased the ability of the microorganism to efficiently utilise more recalcitrant substrates, leading to greater C loss, consistent with previous research (Allison et al., 2010; Frey et al., 2013; Wu et al., 2015). Previous studies have reported that recalcitrant OC fractions have a higher temperature sensitivity than labile OC fractions in most terrestrial ecosystems (Karhu et al., 2010; Sihi et al., 2016; Yuste et al., 2007). Ylla et al. (2012) suggested that labile OM might be utilised preferentially and rapidly when it is available, but its effects quickly dissipated, and the microbial use of the degradation products from humic substances and hemicellulose is enhanced at the higher temperature. Recalcitrant OC fractions comprise more biochemically complex compounds than labile OC fraction, so that it has greater activation energy (von Luetzow and
Fig. 5. Changes of the Fmax values of the four components identified by PARAFAC in DOM solutions from sloped cropland, grassland, shrubland and woodland during 60-day incubation at different temperatures. Error bars represent one standard deviation (n = 3).

Table 3
Correlation coefficients among soil and litter properties, initial DOM composition indices and with incubation DOC and DON losses.

<table>
<thead>
<tr>
<th></th>
<th>Total soluble polyphenolics</th>
<th>Acid insoluble lignin</th>
<th>Cellulose</th>
<th>SUVA254</th>
<th>SUVA280</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>DOC/DON</th>
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<tbody>
<tr>
<td>DOM solutions incubated at 35°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DOC loss</td>
<td>0.252</td>
<td>−0.201</td>
<td>0.1</td>
<td>−0.837**</td>
<td>−0.844**</td>
<td>−0.756**</td>
<td>0.477</td>
<td>−0.304</td>
<td>0.338</td>
<td>0.094</td>
</tr>
<tr>
<td>TDN loss</td>
<td>−0.34</td>
<td>−0.751**</td>
<td>−0.513</td>
<td>−0.511</td>
<td>−0.519</td>
<td>−0.572</td>
<td>0.930**</td>
<td>0.514</td>
<td>0.889**</td>
<td>0.338</td>
</tr>
<tr>
<td>DON loss</td>
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<td>−0.047</td>
<td>−0.621</td>
<td>0.449</td>
<td>0.444</td>
<td>0.439</td>
<td>0.314</td>
<td>0.722**</td>
<td>0.389</td>
<td>0.360</td>
</tr>
<tr>
<td>DOC/DON</td>
<td>0.094</td>
<td>0.338</td>
<td>0.360</td>
<td>−0.024</td>
<td>−0.039</td>
<td>0.073</td>
<td>0.499</td>
<td>0.445</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>DOC loss</td>
<td>0.536</td>
<td>0.388</td>
<td>0.564</td>
<td>0.066</td>
<td>0.079</td>
<td>0.081</td>
<td>−0.740**</td>
<td>−0.684</td>
<td>−0.802**</td>
<td>−0.762**</td>
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<td>−0.005</td>
<td>−0.870**</td>
<td>−0.369</td>
<td>−0.694*</td>
<td>−0.704*</td>
<td>−0.712**</td>
<td>0.859**</td>
<td>0.250</td>
<td>0.673*</td>
<td>0.309</td>
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<tr>
<td>DON loss</td>
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<td>−0.710*</td>
<td>−0.587</td>
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<td>0.434</td>
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<td>0.505</td>
<td>0.824**</td>
<td>0.504</td>
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<td>−0.039</td>
<td>0.073</td>
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<td>DOC loss</td>
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<td>0.463</td>
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<td>0.734**</td>
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<td>0.356</td>
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<td>0.784**</td>
<td>0.759**</td>
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<td>0.499</td>
<td>0.445</td>
<td>0.446</td>
<td>−0.120</td>
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</tbody>
</table>

Note: * correlation is significantly different at the 0.05 level (2-tailed); ** correlation is significantly different at the 0.01 level (2-tailed).
Koegel-Knabner, 2009). OC decomposition reaction with higher activation energy has higher temperature sensitivity based on Arrhenius equation, therefore temperature sensitivity of OC decomposition increases with the substrate recalcitrance (Conant et al., 2011; Mao and Li, 2018; Yuste et al., 2007).

The rate of the biodegradation of the DOC was the highest during the first day and subsequently decreased rapidly during days 1 to 7, consistent with previous research (Ghani et al., 2013; Sanderman et al., 2011). The biodegradation of the DOC and initial rate of biodegradation for all four land-use types increased as the temperature rose. Generally, the mineralization rate constants of the labile and stable DOC pools were the lowest at 4°C for all four land-use types. This phenomenon is due to dramatic increases in microbial and enzymatic activities with rising temperatures (German et al., 2012; Stone et al., 2012; Trasar-Cepeda et al., 2007). The half-life of the stable DOC pool that was sensitive to temperature varied between 7 d and 288 d, while the half-life of the labile DOC pool that was less sensitive to temperature varied between 1.5 and 5.7 d, consistent with previous studies (Boddy et al., 2008; von Lutzow and Koegel-Knabner, 2009). The TDN losses after 60-day incubation were not significantly affected by temperature for any of the four land-use types. The TDN pool is comprised of DON and dissolved inorganic N that is used by heterotrophs and autotrophs, respectively. The activity of these two types of microorganisms might react differentially to warming, thus contributing to the insensitivity of the TDN biodegradability to temperature. The DON losses after the 60-day incubation were the lowest at 4°C, similar to the DOC losses, indicating that low temperature decreases DON biodegradation. The DON losses in the grassland and shrub land were the highest at 20°C, indicating that the most suitable temperature for the decomposition of the DON is 20°C. As discussed previously, tryptophan-like fluorescence is a useful indicator of biodegradable DON. The contents of this material from the sloped cropland, grassland and woodland were the lowest at 20°C and the highest at 4°C, confirming that the DON was easily degraded at 20°C but barely degraded at 4°C. In addition, negative correlation was observed at 20°C between DON loss after 60-day incubation and litter acid insoluble lignin, but positive correlation was observed between them at 4°C. This result implied that the biodegradation of DON at 20°C was limited by acid insoluble lignin, and the decomposition of acid insoluble lignin was promoted at 20°C relative to 4°C. A previous study found that the most suitable temperature for microbial nitrification varied from 25°C to 35°C (Brady and Weil, 1999). In this study, the dynamics of NO3⁻ were not significantly affected by temperature (Table 7), but the NH4⁺ contents dramatically increased with temperature, indicating that high temperature stimulated microbial ammonification.

The dynamics of the biodegradation of the TDN correlated significantly with those of the DOC at 35°C. However, this was not the case for the grassland, shrub land, and woodland at 20°C or for all four land-use types at 4°C. Moreover, the dynamics of the DON decomposition lacked a significant correlation with the DOC dynamics at any of the three temperatures. Previous studies also observed that the DOC and DON dynamics can have either similar (Cleveland et al., 2004; Klikkila et al., 2006; Schmidt et al., 2011) or divergent (Ghani et al., 2013; Gregorich et al., 2003) trajectories during the biodegradation of the DOM. The divergent trajectories between the dynamics of DOC, TN, and DON may be due to the accumulation of dissolved organic C and N in the different DOM fractions such as hydrophobic and hydrophilic, respectively (Petrone et al., 2009; Schmidt et al., 2011). Besides, the hydrophobic acidic fraction is less degradable than the hydrophilic neutral fraction (Jandl and Sollins, 1997; Kalbitz et al., 2003a). In this study, the biodegradability of DON was generally higher, and the most suitable temperature for the decomposition of the DON is lower than that of the DOC, confirming that the DON is more recalcitrant than the DON. Rising temperature can increase the efficient use of more recalcitrant substrates, and organic matter with higher bioavailability can rapidly be cycled regardless of temperature (Allison et al., 2010; Frey et al., 2013; Ylla et al., 2012). Different use efficiencies of the hydrophobic acidic and hydrophilic neutral fractions by microbes at different temperatures were thus likely to be the key factor causing the divergence in the biodegradation of the DOC and TDN. 4.3. Effects of the interaction between temperature and revegetation on soil DOM biodegradation

The half-lives of the labile pools were the lowest at 20°C, indicating that the most suitable temperature for the decomposition of the labile DOC was at 20°C. However, the most suitable temperature for the decomposition of the stable DOC pools differs between the land-use types. Moreover, DOC were more stable and contained more recalcitrant substances in the shrubland and woodland relative to sloped cropland and grassland, but the DON biodegradation has higher temperature sensitivity for the sloped cropland and grassland than that of the shrub land and woodland (Table 5). As discussed above, the decomposition of biogeochemically recalcitrant organic matter that requires a higher activation energy to be degraded should generally be more sensitive to changes in temperature than the decomposition of more labile organic matter (Craine et al., 2010), which is opposite to our results. The previous study considered that the relative abundance and diversity of bacteria and fungi was the dominant factor influencing the temperature sensitivity of SOC decomposition (Liu et al., 2017). Fungi are more likely to decompose recalcitrant SOM that requires higher activation energy (Liu et al., 2017; Malik et al., 2016; Paterson et al., 2016; Shab et al., 2016). The afforestation in the Loess Plateau increased the amounts of root and litter biomass that resulted in enhanced bacterial abundance and diversity (Ren et al., 2016a; Ren et al., 2016b; Tian et al., 2017) but did not significantly alter the abundance and diversity of fungi (Ren et al., 2016b; Tian et al., 2017). The low fungi:bacteria ratio after afforestation induced a low efficiency in decomposing DOM, resulting in the low temperature sensitivity. Additionally, the DON biodegradation in the sloped cropland during the 60 day incubation period at 4°C - 35°C varied from 5.8% to 22.8%, from 42.7% to 79.4%, and from 61.9% to 71.3% in the sloped cropland, grassland and woodland, respectively. This result indicates that the conversion of the sloped cropland to woodland decreases the sensitivity of DON biodegradation to temperature. 5. Conclusions

This study investigated the effects of interaction between temperature and revegetation on DOM decomposition. Revegetation increased the amount of recalcitrant substances in the DOM that increased the stable DOC pool and reduced the decomposition of the DOC. Revegetation, however, increased the amount of tryptophan-like component that promoted the biodegradation of the DON. Rising temperature initially promotes the decomposition of tryptophan-like material, and later promotes the degradation of more recalcitrant substances, such as humic-like material and fulvic acid, which enhanced the decomposition of the DOC and DON. The biodegradability of the DON was higher and more sensitive to temperature than that of the DOC. The conversion of sloped cropland to shrub land and woodland decreased the temperature sensitivity of the DOC decomposition.

### Table 4

<table>
<thead>
<tr>
<th>DOM solutions</th>
<th>Linear equation</th>
<th>R²</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sloped cropland at 35°C</td>
<td>Y = 0.348x - 6.670</td>
<td>0.861</td>
<td>P &lt; 0.001</td>
</tr>
<tr>
<td>Grassland at 35°C</td>
<td>Y = 0.192x + 13.540</td>
<td>0.780</td>
<td>P &lt; 0.005</td>
</tr>
<tr>
<td>Shrubland at 35°C</td>
<td>Y = 0.235x - 7.83</td>
<td>0.859</td>
<td>P &lt; 0.001</td>
</tr>
<tr>
<td>Woodland at 35°C</td>
<td>Y = 0.313x + 5.857</td>
<td>0.850</td>
<td>P &lt; 0.001</td>
</tr>
<tr>
<td>Sloped cropland at 20°C</td>
<td>Y = 0.279x + 1.003</td>
<td>0.822</td>
<td>P &lt; 0.001</td>
</tr>
</tbody>
</table>

X: TDN concentration; y: DOC concentration.
Temperature can cause the divergence between the dynamics of DOC and TDN biodegradation. The results suggest that the conversion of sloped cropland to shrub land and woodland not only promoted the accumulation of DOC, TDN, and recalcitrant substances in DOM solution, and decreased their biodegradability but also decreased the temperature sensitivity of the decomposition of the DOM and DON. This finding indicates that shrub land and woodland are the optimal choices for revegetation in the Loess Plateau of China. Further research should investigate the temperature effects on microorganisms during soil DOM decomposition using stable isotopic carbon and nitrogen.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2018.10.041.

References