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Long-term straw decomposition in agro-ecosystems described by a unified three-exponentiation equation with thermal time

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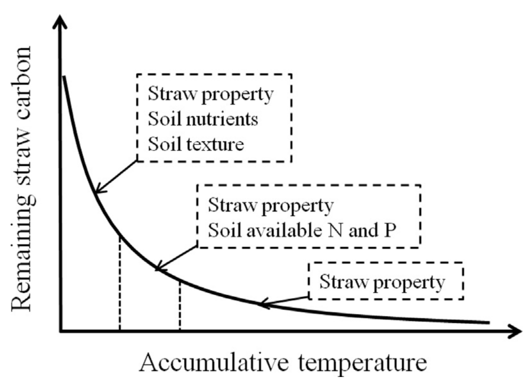
HIGHLIGHTS

- Long-term straw decomposition driven by temperature and straw quality
- The remaining carbon of six straw has difference under one thermal year.
- The effects of soil property on the straw decomposition differ at different stages.
- The amount of remaining straw C was 29.41 Tg under one thermal year.
- Temperature increase of 2 °C could reduce the remaining straw C by 1.78 Tg.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding drivers of straw decomposition is essential for adopting appropriate management practice to improve soil fertility and promote carbon (C) sequestration in agricultural systems. However, predicting straw decomposition and characteristics is difficult because of the interactions between many factors related to straw properties, soil properties, and climate, especially under future climate change conditions. This study investigated the driving factors of straw decomposition of six types of crop straw including wheat, maize, rice, soybean, rape, and other straw by synthesizing 1642 paired data from 98 published papers at spatial and temporal scales across China. All the data derived from the field experiments using little bags over twelve years. Overall, despite large differences in climatic and soil properties, the remaining straw carbon (C, %) could be accurately represented by a three-exponent equation with thermal time (accumulative temperature). The lignin/nitrogen and lignin/phosphorus ratios of straw can be used to define the size of labile, intermediate, and recalcitrant C pool. The remaining C for an individual type of straw in the mild-temperature zone was higher than that in the warm-temperature and subtropical zone within one calendar year. The remaining straw C after one thermal year was 40.28%, 37.97%, 37.77%, 34.71%, 30.87%, and 27.99% for rice, soybean, rape, wheat, maize, and other straw, respectively. Soil available nitrogen and phosphorus influenced the remaining straw C at different decomposition stages. For one calendar year, the total amount of remaining straw C was estimated to be 29.41 Tg and future temperature increase of 2 °C could reduce the remaining straw C by 1.78 Tg. These findings confirmed the long-term

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straw decomposition could be mainly driven by temperature and straw quality, and quantitatively predicted by thermal time with the three-exponent equation for a wide array of straw types at spatial and temporal scales in agro-ecosystems of China.

1. Introduction

Increasing atmospheric carbon dioxide (CO_2) concentration is expected to contribute to global warming (Smith and Fang, 2010; Tian et al., 2016). Previous work has suggested that agricultural soils can serve as a potential sink for atmospheric CO_2 by sequestrating soil carbon (C) (Lal, 2004; Schmidt et al., 2011). Crop residues such as wheat straw are a global resource with potential for contributing to soil C stocks and mitigating climate change (Liu et al., 2014; Lu, 2014). Straw return not only directly increases C input into the soil, but also improves soil physical and biochemical properties that are essential to crop growth (Lal, 2008; Liu et al., 2014). The rate of straw decomposition determines how fast the CO_2 is returned to atmosphere and ultimately the soil C stocks. Therefore, understanding the drivers of straw decomposition is critical for adjusting the accuracy of climate change models, mitigating climate change, and preserving ecosystem functions (Lin, 2014; Luo et al., 2015).

Straw decomposition is primarily controlled by the climate conditions, straw quality, and soil properties (Wang et al., 2012). Climate conditions such as temperature and precipitation are critical factors that control the straw decomposition on a large geographical scale (Gregorich et al., 2016). Many studies have found a strong linear relationship between the decomposition rate constant and mean temperature (Zhang et al., 2008; Wang et al., 2012). At ten sites spanning a 3500-km transect across the agricultural regions of Canada, Gregorich et al. (2016) found thermal time (accumulative temperature) accurately described kinetics of straw decomposition over five years. The different straw quality has long been thought to determine the decomposition rates (Wang et al., 2012). Using compound-specific isotopic analysis, molecules predicted to persist in soils (such as lignin or lipid) has been shown to turn over more slowly than the labile compounds (such as sugars) (Schmidt et al., 2011). The effect of properties such as soil nutrients and texture to the straw decomposition rate is indirect (Zhang et al., 2008; Ge et al., 2013). Over the five years, soil organic C, soil texture, pH and moisture had minimal discernible influence on decomposition kinetics over five years (Gregorich et al., 2016). The decomposition rate was positively correlated with soil nutrients, in nutrient rich soil with fast rate and nutrients was easy to retention in early stages of decomposition (Ge et al., 2013). The effects of soil properties on the straw decomposition may differ at different decomposition stages. However, the responses of these factors to straw decomposition remain uncertain, especially at spatial and temporal patterns in agro-ecosystems.

Predicting straw decomposition is difficult because they not only relate to many interacting factors but also depend on the equations of choice (Prescott, 2010; Derrien and Amelung, 2011). Many empirical equations based on physical and chemical heterogeneity of the original material have been proposed to estimate straw decomposition (Feng and Li, 2001; Adair et al., 2008). Although these empirical equations have been widely used and provided useful information on straw decomposition and soil C cycling, the results are difficult to extrapolate under different conditions (Adair et al., 2008; Prescott, 2010). First, most studies involved one site or a low diversity of crop straw types and chemistries, making it less representative at larger scales (Gholz et al., 2000; Gregorich et al., 2016). Second, many studies were conducted for less than five years, which might be not long enough to reveal the dynamics of straw decomposition during later phases (Amin et al., 2013). Finally, due to different starting times of the various straw decomposition experiments, seasonal and high-frequency temperature variability cannot be neglected (Manzoni et al., 2012). Therefore, these factors should be considered when choosing the best equation and using big data both to accurately describe straw decomposition and to extrapolate to spatial patterns for different crop systems.

The characteristics of straw C fraction that remain in the soil after one calendar year are referred to as the humification coefficient, which is an indicator of remaining straw C. This humification coefficient is important for estimating the amount of stable organic C and soil C sequestration potential as well as evaluating the parameterization of models (Janssen, 1984; Galvez et al., 2012). Complete humification of organic material can be accomplished after one calendar year or more, since humification depends on the soil nutrient status, organic material properties, and climatic conditions (Guo and Lin, 2001; Cai and Qin, 2006). The humification coefficient is not a constant value for identical organic materials under different conditions. The results of different studies are usually difficult to compare and use. Therefore, understanding the humification coefficient value under different conditions is very important to better understanding of soil C cycling in agro-ecosystems.

In this study, we used a comprehensive dataset to accurately describe the long-term straw decomposition and characteristics at spatial and temporal patterns in agro-ecosystems. We explored the straw decomposition and characteristics from 1642 straw decomposition data points paired with daily temperature from 92 climatic stations of China, spanning different straw types, soil properties, and climate conditions. Our specific objectives were: (i) to quantify the effect of thermal time on the six common crop straw decomposition at agro-ecosystems; (ii) to compare the characteristic of six straw types decomposition among different climate zones, and (iii) to assess the relative importance of soil properties drivers of straw decomposition during the different decomposition stages.

2. Materials and methods

2.1. Literature search and data sources

We searched the Web of Science (http://apps.webofknowledge.com) and China Knowledge Resource Integrated Database (http://www.cnki.net/) for papers published on straw decomposition through December 2016. Specific keywords included "the remaining straw C" or "decomposition and cropland in China". To avoid publication bias, the following criteria were established: (i) Agronomic field experiments were included, but incubation experiments were excluded; (ii) The reports clearly stated the specific timing of the remaining straw C in litterbags; (iii) The remaining straw C data were reported in the form of figures or tables (The data presented as equations were ignorEd.); (iv) At least three measurement values were included during experiments, and one of the values must be within one year; and (v) Experiments were not supplemented with anthropogenic factors, such as the addition of fertilizer, to accelerate or decelerate the buildup of remaining straw C.

From these studies, we directly obtained the remaining straw C percentages (%) as well as their corresponding times (from tables in those studies). Get Data Graph Digitizer 2.24 software was used to indirectly obtain data from the graphs. In these studies, the data were presented as the remaining straw C concentration instead of the percentage of remaining straw C. We estimated the percentage of remaining straw C according to the initial and remaining straw C densities. The data reported in terms of straw C decomposition were converted to the percentage of C remaining by taking the difference between 100 and the percentage of