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Review

# A global perspective on agroecosystem nitrogen cycles after returning crop residue

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ABSTRACT

The return of crop residue to the soil has been suggested as a nutrient-conserving practice that effectively increases soil fertility and crop nutrition. However, the overall direction and magnitude of changes in the agroecosystem nitrogen (N) cycle in response to crop residue return are poorly quantified. In the present study, a global synthesis was performed to assess the effects of crop residue return on 17 variables associated with agroecosystem N cycles, including N pools, N fluxes, and other related parameters. The results showed that crop residue return stimulated crop yield by 5.5%, and N pool sizes in soil, crop, and microbes by 10.7%, 20.8%, and 34.9%, respectively, suggesting that this technique functions to conserve N, improve soil fertility, and optimize N supply for agricultural crop-soil systems. These responses were positively affected by the rate and duration of residue application, suggesting that the effects of crop residue return may be cumulative. Moreover, crop residue return had no effect on $N_2O$ emission and N leaching when all agroecosystems were assessed, but when upland fields were separately assessed, they showed an increase in $N_2O$ emission (+16.6%) and a decrease in N leaching (−9.1%). However, the stimulatory effect on $N_2O$ emission in upland fields was much lower than the effect seen with fertilizer use (+117.2%). There was no positive relationship between residue return rate and $N_2O$ emission. The addition of N fertilizer could inhibit the stimulatory effect of crop residue return on the crop yield and soil total N pool. The challenge for modern agriculture to meet the food demands of a growing population will require sustainable practices. Given the low return rate of crop residue at present, these results emphasize the importance of using this environmentally friendly practice to enhance the sustainability of agriculture and reduce agricultural pollution.

## 1. Introduction

The global population is projected to reach 9.1 billion by 2050 (UN, 2017), which poses an impending threat to global food security and environmental sustainability. Managing nutrient balance in agroecosystems is critical for the maintenance and production of crops to meet increasing food demands (Vitousek et al., 2009). Harvested crops remove crop-derived nitrogen (N) from agricultural soil over the years and, as a result, modern agriculture has become increasingly dependent on chemical fertilizers to offset nutrient deficiencies in agroecosystems; it is regarded as the most effective method to achieve this goal (Frink et al., 1999). Based on past trends, global N fertilization is projected to reach 236 $10^6$ MT per year by 2050 (Tilman et al., 2001). However, excessive inputs of fertilizers to agroecosystems can have substantial environmental consequences, particularly from the cascading effects of reactive N, which, in turn, can compromise human well-being (Vitousek et al., 2009; Drinkwater and Snapp, 2015). The Food and Agricultural Organization of the United Nations (FAO) has highlighted the need to increase food production without environmental degradation and has proposed environmentally sustainable agricultural practices as the means to achieve this aim (FAO, 2017).

Crop residue is a renewable resource and the return of these residues to the soil is a nutrient-conserving practice that increases crop production and soil fertility, and has been utilized in agricultural practices since ancient times (Bailey and Lazarovits, 2003). Numerous meta-analyses have examined the effects of crop residue return on both soil C storage (Huang et al., 2013; Miguez, 2015; Tian et al., 2015; Li et al., 2017) and C fluxes (Sanchis et al., 2012; Lehtinen et al., 2014; Liu et al., 2014) in agroecosystems. However, relatively little is known about the effects of crop residue return on N pools and fluxes, which

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exert a substantial influence on crop yield and soil fertility (Galloway et al., 2008; Liu et al., 2014). It is imperative to comprehensively examine how the agroecosystem N cycle responds to crop residue return to improve the ability to utilize crop residue in agroecosystems.

Although numerous individual studies have been conducted to examine how the agroecosystem N cycle responds to crop residue return, the experimental results from these studies are highly variable, which hampers the ability to draw firm conclusions on the efficacy of crop residue return. For example, previous studies have demonstrated that the decomposition of crop residues stimulated soil microbial activity, accelerating soil N cycling by improving soil N availability (Bending et al., 2002), and consequently increasing crop yield (Smil, 1999; Liu et al., 2014). However, other studies have shown that crop N uptake, soil mineral N concentration, and microbial biomass N were reduced or unaffected by crop residue return (Soon, 1998; Takahashi et al., 2003). In addition, there are some concerns about the potential negative effects of crop residue return on agricultural environments. For example, the variation in soil physical and chemical properties induced by crop residue can mediate N leaching and $N_2O$ emission (Mitchell et al., 2000; Toma and Hatano, 2007), which can contribute to cascading consequences of reactive N (Galloway et al., 2004). Therefore, it is necessary to assimilate results across studies to identify general patterns of agroecosystem N pools and fluxes after returning crop residues.

Many factors can influence the response of agroecosystem N cycles to crop residue return. For example, the residue input rate is positively correlated with soil N immobilization (Masciandaro et al., 2004; Zhang et al., 2015, 2016). The $N_2O$ emission and N uptake in paddy fields are significantly higher than in upland fields (Takahashi et al., 2003; Nishimura et al., 2011). In addition, residue placement methods, such as incorporation and mulching, can regulate the efficacy of crop residue return by influencing soil physical properties, aggregate formation, soil moisture, and temperature (Mandal et al., 2015). Other factors, such as chemical N application rate (Sharma and Prasad, 2010) and return duration of crop residue (Uhlen, 1991) are also important in assessing the changes in crop-soil N cycling after crop residue return. Therefore, there is a critical need to assess the effects of crop residue return on the agroecosystem N cycle under different types of agroecosystems and management strategies; the results of which will greatly benefit the development of proper straw use and contribute to agricultural sustainability.

Here, we present a global synthesis of the agroecosystem N cycle in response to crop residue return so that the efficacy of this practice for agricultural sustainability can be rigorously evaluated. Based on an extensive literature search, data were compiled from 156 individual studies (Table S1) that investigated the responses of 17 variables (e.g., total crop and soil N pools) related to the N cycle and crop residue return. As these studies were globally distributed and considering that various agroecosystems may respond differently to crop residue return, the efficacy of crop residue return was evaluated in upland fields (aerobic agroecosystem mainly cultivated with corn and wheat) and paddy fields (anaerobic agroecosystem cultivated with rice), separately. The study also tested whether critical management strategies (i.e., crop residue return rate, return duration, placement, and fertilization) affect the efficacy of crop residue return.

## 2. Materials and methods

### 2.1. Data sources

Data were compiled from 156 published experimental studies (Table S1) by extensively searching Google scholar, Web of Science (1900–2017), China Knowledge Resource Integrated Database (available online), and Baidu scholar. To avoid bias in publication selection, the following five criteria were set for the inclusion of data related to the response of agroecosystem N cycles to crop residue return: (1) the experimental duration and land use were clearly recorded and the measurements of treatment and control groups were conducted within the same temporal and spatial scales; (2) crop residue was added directly to the agroecosystem and paired data (control and treatment) for at least one of the chosen variables was reported; (3) studies with an experimental duration less than one year were excluded to avoid short-term noise; (4) the control and treatment plots started with the same soil type, N fertilizer application rate, climatic conditions, crop species, and other conditions. Thus, some sample sizes exceeded 156 because some experimental studies had more than one treatment; (5) the primary data—from which means, standard deviations (*SD*), or standard errors (*SE*), and sample sizes ($n$) could be calculated—were directly provided or these statistics could be calculated from the results. To meet the statistical assumption of independence among observations, the final data were extracted measurements when the chosen variables were presented at multiple time points (Treseder, 2008). In addition, because management strategies may confound the response of crop-soil N cycling to crop residue return, we categorized land use types (i.e., paddy and upland fields), experimental duration (i.e., 1–3, 3–15, > 15 y), and placement methods (i.e., incorporation and mulching).

The compiled database included four aspects of the agroecosystem N cycle: (1) crop [including crop yield and crop total nitrogen (CTN)], crop N uptake (calculated as the percentage of N content in the dry matter yield of crop organs), N use efficiency (NUE, calculated as the ratio of crop N uptake relative to the total N application); (2) soil [including soil total nitrogen pool (STN)], soil C:N ratio, soil mineral N concentration (SMN, calculated as the increase in inorganic N during the incubation), soil inorganic nitrogen pool (SIN), $NH_4^+$ and $NO_3^-$ concentrations, total organic nitrogen pool (TON), dissolved organic nitrogen pool (DON), light fraction organic nitrogen pool (LFON); (3) microbes [including microbial biomass nitrogen (MBN), microbial biomass C:N ratio]; (4) pollutants (including $N_2O$ and N leaching).

### 2.2. Data synthesis

The data were synthesized using meta-analytic techniques (Hedges et al., 1999; Rosenberg et al., 2000), which enabled us to summarize the results of multiple independent studies using a mixed-effects model meta-analysis, and to compare multiple classes using cumulative effect sizes and confidence intervals. In the random-effects, we assumed that the true effects were normally distributed, whereas the weights fell within a relatively narrow range. To calculate the effect size of crop residue return treatments ($\log_e RR = \log_e (\overline{Xt}/\overline{Xc})$; Table S2), where $\overline{Xc}$ is the control mean and $\overline{Xt}$ is the treatment mean, the natural log-transformed response ratio ($\log_e RR$) of each crop-soil cycling variable was used. The average response ratio was calculated using the mixed model of the meta-analytical software, METAWIN 2.0 (Sinauer Associates, Inc. Sunderland, MA, USA). The variance in the mean effect size was calculated using resampling methods (Adams et al., 1997). If the 95% CI value of $RR_{++}$ for a response variable overlapped with zero, the response ratio was not significant. To test the influence of categorical classes, the total heterogeneity among groups ($Q_t$) was partitioned into within-group heterogeneity ($Q_w$) and between-group heterogeneity ($Q_b$). A significant $Q_b$ indicated that there were differences in the effect size of crop residue return treatments between the different classes of a variable. Under the random-effects model, the weights fall in a relatively narrow range. Generally, interpretation of a parametric random-effects meta-analysis is formally in the context of an imaginary 'universe' from which the effects in the observed studies are independently and identically sampled. Although such an infinite population does not exist in reality, the construct allows inference about treatment effects to be extended to a broader population than the studies at hand. To check for publication bias, the frequency distributions of variables were characterized by Gaussian normal distributions (Rosenberg et al., 2000) to reflect the normality of residue return effects among different studies using Sigma Plot 11.0 (Systat Software Inc., USA) (Table S3). Regression analyses were used to examine the relationships of $\log_e RR$ of the