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REVIEW ARTICLE

Soil nitrogen dynamics and crop residues. A review

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Abstract Nitrogen (N) is a major fertiliser for agriculture and food production. About 67.84 million tons of N are annually applied to agricultural fields, without which nearly half of the world's population would not be alive today. Returning plant residues to the soil is an alternative and sustainable way of N fertilisation. Although impacts of returning plant residues on plant available N in soil have been widely studied, there is still no systematic review of their mechanisms and models. In this review we highlight the following advances: (1) When plant residues are returned to the soil, N undergoes biotic immobilisation–remineralisation, abiotic immobilisation, soil organic N mineralisation and plant residue organic N mineralisation. (2) Plant residues modify inorganic N fate using three mechanism mineralisation, immobilisation–mineralisation and immobilisation, depending on plant residue nature and soil properties. (3) The use of plant residue C/N ratio is not always effective to predict the effect of plant residues. Instead, soil properties and the forms of carbon and nitrogen should be considered. (4) Mineralisation always promotes N uptake by crops and increases the risk of N loss. In addition, although net immobilisation is involved in immobilisation–mineralisation and immobilisation, it does not necessarily induce lower crop nitrogen uptake. Results also depend on the synchronism between the changing soil inorganic N and the crop N uptake. (5) N loss during mineralisation can be reduced by an immobiliser. Net N immobilisation during immobilisation–mineralisation and immobilisation can be reduced by changing the timing of ploughing and fertilising or by changing the plant residues placement.

Keywords Inorganic nitrogen · Plant residues · Crop nitrogen uptake

Contents

B. Chen · E. Liu (✉) · C. Yan · Y. Zhang
Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing 100081, People's Republic of China
e-mail: liuenke@caas.cn

B. Chen · E. Liu · C. Yan · Y. Zhang
Key Laboratory of Dryland Farming Agriculture, Ministry of Agriculture of the People's Republic of China (MOA), Beijing 100081, People's Republic of China

Q. Tian
State Key Laboratory of Crop Biology, Shandong Agriculture University, Tai'an, China

1 Introduction

Nitrogen is one of most important elements for sustaining human life. Every year, about 67.84 million tons of nitrogen is applied to agricultural land all over the world (Liu et al. 2010). The total cost is up to $44.2 billion. Nitrogen from ammonia, various synthetic nitrogen fertilizers are manufactured, without which nearly half of the world's population would not be alive today (Erisman et al. 2008). However, synthetic N fertilizer has become "too much of a good thing" because much of the N applied to cropland escapes the agricultural system and becomes a pollutant (Sutton et al. 2011). It is important to better understand the influence of different agricultural practices on soil mineral N dynamics to improve its use efficiency and reduce pollution.

Returning plant residue to the soil (Fig. 1) is an effective method for sustaining soil organic matter concentration, enhancing biological activities, improving physical properties and increasing nutrient availabilities (Smith et al. 1992). Organic matter is an essential soil component that is greatly affected by plant residue management. When plant residue or other organic sources are not returned to a soil, the soil biological fertility and resilience decreases as the physical, chemical and biological properties of the soil decline (Lal 1994; Kirchner et al. 1993; Wood and Edwards 1992; Perucci et al. 1997). This process results in low soil productivity. Moreover, large N, P, K and other nutrient concentrations can be available in plant residues for plant growth, which can improve long-term plant productivity. In addition, the return of plant residues to the soil can improve soil physical properties, which can reduce soil erosion risks (Freebairn and Boughton 1985; McGregor et al. 1990; Cassel et al. 1995) and improve the soil moisture retention (Bussière and Cellier 1994; Gill and Jalota 1996). Based on these benefits, more plant residues are being returned to farmlands throughout the world.

Soil inorganic nitrogen, which is derived from fertiliser nitrogen and soil organic nitrogen mineralisation, is the main form of plant available nitrogen. Historically, the relationships between plant residue quality and soil N dynamics have not been considered as important (Havlin et al. 1990). However, recent research has indicated that the properties of the returned plant residues influence the inorganic soil nitrogen concentrations. For example, higher quality plant residues, that are with

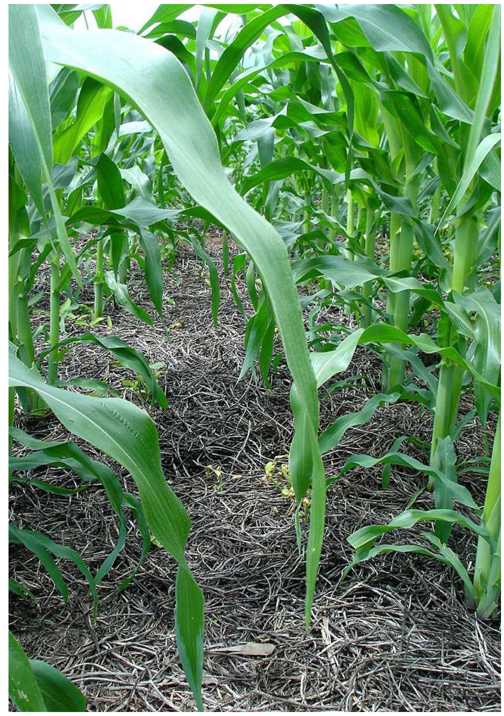

Fig. 1 Returning plant residues in the field. This widely applied agricultural practice can significantly improve soil quality and has uncertain influences on soil nitrogen dynamics

high N concentrations, low lignin and cellulose concentrations and low C:N and lignin:N ratios often result in high N mineralisation rates. In contrast, low-quality residues have a lower N mineralisation rate that can negatively influence plant available nitrogen due to their effect on nitrogen immobilisation (Chaves et al. 2004; Gentile et al. 2009; Manzoni et al. 2008). Furthermore, changing inorganic nitrogen concentrations will affect the assimilation of nitrogen by plants and the potential nitrogen loss (Ichir and Ismaili 2002; Trinsoutrot et al. 2000; Sugihara et al. 2012). The changing inorganic nitrogen concentrations in plant residues that are returned to the soil and the crop nitrogen demand pattern have been widely studied recently. However, few systematic understanding regarding the mechanisms, process types and resulting quantitative models of soil inorganic nitrogen following the return of plant residues to soils has been established. In addition, the synchronism between different changing soil inorganic nitrogen process types and crop nitrogen uptake has not been determined. Here, the inorganic nitrogen changes that are caused by plant residues are defined as the differences between the soil inorganic nitrogen concentrations in soils with and without plant residues. Based on this definition, the objectives of this article are as follows: (1) to summarise the different inorganic nitrogen pathways during the return of plant residues; (2) to generalise different changing inorganic nitrogen process types and their classification standards; (3) to summarise the development of quantitative prediction models based on detailed indicators; (4) to assess the effects of inorganic nitrogen changes on crop nitrogen uptake and to establish a conceptual and quantitative model for the future; and (5) to discuss the adjustment measures to enhance the synchronism between inorganic nitrogen accumulation and plant nitrogen assimilation.

2 The influences of plant residues on soil inorganic nitrogen pathways

Soil inorganic nitrogen is derived from nitrogen fertilisers and soil organic nitrogen mineralisation. Inorganic nitrogen is subjected to a series of biochemical transformations in plant residues that are returned to the soil. Without considering the indirect influences of plant residues on soil nitrogen losses through leaching, runoff, denitrification, ammonification etc., four processes were found to influence the inorganic nitrogen pathways in soils with plant residues, including biotic immobilisation–remineralisation, abiotic immobilisation, soil organic nitrogen mineralisation and plant residue organic nitrogen mineralisation.

2.1 Biotic immobilisation–remineralisation

Plant residues deposited on soils are subject to biological degradation (Berg and McClaugherty 2008). During biological degradation, plant residue carbon is used in respiration by decomposers, which releases CO_2 and provides energy. With this energy source, microbial communities absorb different nutrients from the soil to promote their propagation. Regarding inorganic soil nitrogen which comes from the mineralisation of soil and fertiliser, if the plant residue nitrogen does not satisfy the microbial growth requirements, it is absorbed by the microbial communities as a nitrogen source, i.e. immobilisation. Consequently, regardless of the C:N ratio or residue placement, above or belowground, all the plant residue that is returned to the field will enhance the microbe biomass nitrogen concentration during the early decomposition stages (Bird et al. 2001; Sakala et al. 2000).

The microbially immobilised inorganic nitrogen supports microbial proliferation and can be reused in suitable environments. This process is referred to as remineralisation, which mainly results from microbial death. Microbial death potentially results from microbe–substrate interactions or from predatory microbial regulation (Zelenev et al. 2006). Regarding microbe–substrate interactions, when the plant residue C or soil nutrient concentrations are not sufficient for microbial proliferations, microbial death will occur. In this case, the microbial biomass nitrogen from the dead microorganisms will become available through enzymolysis. The C:N ratio of bacteria, fungi and their predators are 3.65–4.92, 8–10 and 5.16–6.83 and 8–11, respectively. As a result, the availability of nitrogen by predation results from the high consumption and low assimilation rate of predators (Ferris et al. 1998; Ferris et al. 1997; Griffin et al. 1972; Chen and Ferris. 1999). In this case, ammonium is released from live predators. Shindo and Nishio (2005) found that the remineralisation rates of wheat straw that was returned to the soil were 0.71, 0.55 and 0.29 mg N kg^{-1} day^{-1} after 7, 28 and 54 days, respectively.

The increased inorganic nitrogen immobilisation in microbial biomass does not correspond with the observed decrease in the soil inorganic nitrogen concentration. The negative N balance in soil after incorporating plant residues may result from unknown organic nitrogen fractions, which is considered as microbial residual products, e.g. empty hyphae, dead microbial cell residues and cell exudates (Nishio and Oka 2003; Mueller et al. 1998; Shindo and Nishio. 2005). In addition, Kindler et al. (2009) reported that the N and C from microbial biomass are introduced into soil organic matter as microbial residues after cell death.

2.2 Abiotic immobilisation

Previously, researchers have indicated that nitrogen immobilisation is a biotic process (Mary et al. 1996; Frey et al. 2000). However, many researchers (Dail et al. 2001; Compton and Boone 2002) have recently shown that some ^{15}N-nitrate is removed from the extractable inorganic-N pool in sterilised soils. This nitrogen is subsequently detected in the soluble organic N fraction. This phenomenon is explained by the abiotic conversion of NO_3^- into dissolved organic N (Davidson et al. 2003). However, the effects of plant residues on this abiotic conversion have not been determined. Regardless of the nitrogen conversion process, inorganic nitrogen can be transformed to organic nitrogen directly without existing in microbe biomass. Moreover, some chemical constituents or plant residue decomposition products ,such as phenolic, lignin and tannic acid, can convert soil mineralisable organic nitrogen into recalcitrant nitrogen forms by chemical immobilisation (Shindo and Nishio 2005; Olk et al. 2006). Next, soil inorganic nitrogen may be reduced.

2.3 Soil organic nitrogen mineralisation

Plant residues can affect soil organic nitrogen mineralisation by different mechanisms. These mechanisms were hypothesised from different experimental results. For example, Shindo and Nishio (2005) observed the promotion of organic nitrogen mineralisation by plant residues, which potentially resulted from the increased native organic matter decomposition or from the accelerated microbial biomass N turnover. In contrast, Fontaine et al. (2003) and Bradley and Grenon (2006) observed negative effects, which resulted from the competition between the microorganisms specialised in fresh organic matter decomposition or the use of polymerised soil organic matter for energy and nutrient acquisition.

In addition, when plant residues are returned to the soil surface, the soil environment becomes cooler and wetter than the soil environment of bare soils (Power et al. 1989; Edwards et al. 2000; Ji and Unger. 2001). Consequently, the soil organic nitrogen mineralisation rate may differ (Fang et al.,2007; Tu et al. 2006).

2.4 Organic nitrogen mineralisation of the plant residues

Organic nitrogen mineralisation from plant residues can increase soil inorganic nitrogen concentrations. Shindo and Nishio (2005) found that nearly 10 % of the organic nitrogen that was present in wheat straw was transformed into microbial biomass, and the soil inorganic N concentration which was derived from wheat straw varied between 1.93 and 2.37 mg N kg^{-1}.

Irrespective of N losses from soils with different soil inorganic nitrogen concentrations the direct effects of plant residues on soil inorganic nitrogen are shown in Fig. 2. When plant residues are returned to the soil, the mineralisation of plant residue nitrogen contributes to the soil inorganic nitrogen pool. The extent of this contribution depends on the quality of the plant residue. Although multiple studies have been conducted regarding the effects of plant residues on soil organic nitrogen mineralisation, no generalizations have been made. However, the abiotic immobilisation of nitrogen by plant residues can reduce the concentration of soil mineralisable organic nitrogen. Because the additional inorganic nitrogen in the plant residue is transformed into microbial nitrogen, the microbe biomass nitrogen, the microbial residual nitrogen and the subsequent nitrogen remineralisation rate are enhanced by adding straw residues to soil. However, the effects of plant residues on direct inorganic nitrogen transformations to soil organic nitrogen remain unknown.

Thus, plant residues influence soil inorganic nitrogen concentrations in the four following ways: (1) plant residue nitrogen mineralisation; (2) the uncertain effects of plant residues on soil organic nitrogen mineralisation; (3) increased microbial inorganic nitrogen immobilisation, microbial residual nitrogen and remineralisation rate (abbreviated as effect on microbial nitrogen) and (4) unknown effects on the abiotic transformation of inorganic nitrogen to soil organic nitrogen (abbreviated as abiotic transformation). Based on these mechanisms, we defined the effects of plant residues on soil inorganic nitrogen as shown in formula 1. In addition, the effect of plant residues on soil nitrogen mineralisation can be classified as immobilisation, remineralisation and microbial residual nitrogen. Apart from the residues nitrogen mineralisation, the soil nitrogen mineralisation effect, microbial nitrogen effect and abiotic transformation results can be determined from the priming effect (Kuzyakov et al. 2000). Thus, formula 1 can be expressed by formulas 2 or 3.

$$RE = RNM + SNM + MNE + AT \quad (1)$$

$$RE = RNM + SNM + IME + REE + RNE + AT \quad (2)$$

$$RE = RNM + PE \quad (3)$$

Where RE refers to effect of plant residues on soil inorganic nitrogen; RNM refers to residues nitrogen mineralisation; SNM refers to effect on soil nitrogen mineralisation; MNE refers to effect on microbial nitrogen; AT refers to abiotic transformation; IME, REE and RNE refer to the effect of straw on immobilisation, remineralisation and microbial residual nitrogen, respectively and PE refers to priming effect.

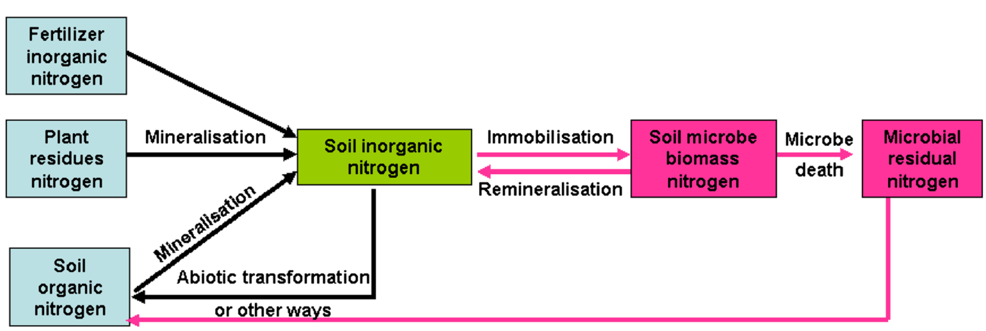

Fig. 2 The direct effect mechanisms of plant residues on soil inorganic nitrogen. Plant residues can provide inorganic to soils through residues nitrogen mineralisation. It is clear now that returning plant residues improve the immobilisation rate, remineralisation rate and microbe death and the corresponding soil microbe biomass nitrogen and microbial residual nitrogen. Influences of straw on soil organic nitrogen mineralisation and the abiotic transform of inorganic nitrogen have not been fully confirmed. These pathways describe how plant residues cause changes in soil inorganic nitrogen

3 Qualitative division and quantitative prediction of changing inorganic nitrogen process types due to plant residues

3.1 Qualitative division

Many studies have examined inorganic nitrogen differences between soils with and without plant residues. These studies indicated that changes in inorganic nitrogen were always linked to the chemical characteristics of the plant residue, especially the C:N ratio. Typically, compared to soils without plant residues, only plant residues with C:N ratios <24 increased the mineral N concentration (Trinsoutrot et al. 2000).

Based on a series of reports (Table 1), three process types were determined regarding the effects of returning plant residues to soils: mineralisation process, immobilisation–mineralisation process and immobilisation process. We define the net immobilisation as decreasing inorganic nitrogen relative to the blank soils, and the net mineralisation as increasing inorganic nitrogen relative to the blank soils. These pathways were classified based on the occurrence and duration of net immobilisation over a limited period (Table 2). For mineralisation process, no net immobilisation occurs. In contrast, net immobilisation occurs in the early stages followed by net mineralisation for immobilisation–mineralisation process. Thus, immobilisation–mineralisation process is characterised by net mineralisation at the end of the experiment. For immobilisation process, no net mineralisation occurs throughout the experiment. A sketch of these patterns is provided in Fig. 3 and descriptions are provided in Table 2. The plant residues with C:N ratios of between 9.4 and 22.7 result in a mineralisation process. These plant residues include residues from vegetables, green manure and leguminous crops. Immobilisation–mineralisation process and immobilization process result from plant residues with C:N ratios of 30.3–136 and 46.5–99.4, respectively. The dividing line between immobilisation–mineralisation process and immobilization process is not absolute (Table 1). For example, wheat straw has a C:N ratio of 79, which results in a immobilisation process curve (Mohanty et al. 2010). However, wheat straw with a C:N ratio of 136 results in a immobilisation–

Table 1 The different observed process types regarding the effects of the returned plant residues on soil inorganic nitrogen within the limited experimental period

Process types	Plant residues	Plant residue C:N ratio	Cultivation time	Reference
Mineralisation process	Red cabbage fine roots	21.6	4 months	Chaves et al. 2004
	White cabbage fine roots	20.7	4 months	Chaves et al. 2004
	Savoy cabbage fine roots	20.5	4 months	Chaves et al. 2004
	Leek roots	11.2	4 months	Chaves et al. 2004
	Ryegrass leaves	12.1	4 months	Chaves et al. 2004
	Ryegrass roots	22.7	4 months	Chaves et al. 2004
	White mustard leaves	9.4	4 months	Chaves et al. 2004
	White mustard stems	19.2	4 months	Chaves et al. 2004
	Alfalfa shoots	–	168 days	Trinsoutrot et al. 2000
	Oilseed rape leaves	–	168 days	Trinsoutrot et al. 2000
Immobilisation–mineralisation process	Red cabbage large roots	30.9	4 months	Chaves et al. 2004
	White cabbage large roots	34.5	4 months	Chaves et al. 2004
	Savoy cabbage large roots	30.3	4 months	Chaves et al. 2004
	Oilseed rape leaves	–	168 days	Trinsoutrot et al. 2000
	Corn residues	32.4	24 weeks	Hadas et al. 2004
	Rice hulls	76.4	24 weeks	Hadas et al. 2004
	Wheat straw	136	24 weeks	Hadas et al. 2004
Immobilisation process	Brussels sprouts large roots	46.5	4 months	Chaves et al. 2004
	Maize straw	–	168 days	Trinsoutrot et al. 2000
	Oilseed rape leaves	–	168 days	Trinsoutrot et al. 2000
	Crop straw	99.4	189 days	Chaves et al. 2005
	Cereal straw	98.7	198 days	Chaves et al. 2006
	Rice straw	86	14 weeks	Mohanty et al. 2010
	Wheat straw	79	14 weeks	Mohanty et al. 2010

Table 2 Feature descriptions of the different inorganic nitrogen change process types that resulted from returning plant residues to the soil

Process types	Net N immobilisation	Net N mineralisation	Final results
Mineralisation process	Non-existent	Exist in all experimental period	Net N mineralisation
Immobilisation–mineralisation process	Exist at early stage	Exist at later stage	Net N mineralisation
Immobilisation process	Exist in all experimental periods	Non-existent	Net N immobilisation

mineralisation process curve (Hadas et al. 2004). Despite these different residue properties, the longer research period used by Hadas et al. (2004) potentially explains this difference. Thus, immobilisation process will not occur if the experimental period is long enough. However, limited crop growth periods cannot provide such a long period, especially in fields where annual plant residues are returned. Based on Table 2, the occurrence time of net mineralisation is a distinguishing standard for mineralisation process, immobilisation–mineralisation process.

If the nitrogen from plant residues is greater than the N demand of the microbial population during plant residue decomposition, plant residues nitrogen mineralization becomes dominant. Inversely, if the N concentrations in the plant residues are low, the inorganic nitrogen will be used by the microbial population and the effect of plant residues on microbial immobilisation becomes dominant.

Manzoni et al. (2008) hypothesised that net nitrogen mineralisation can be calculated as the difference between the total N that is available from litter decomposition and the N that is needed by the decomposers to assimilate C (formula 7).

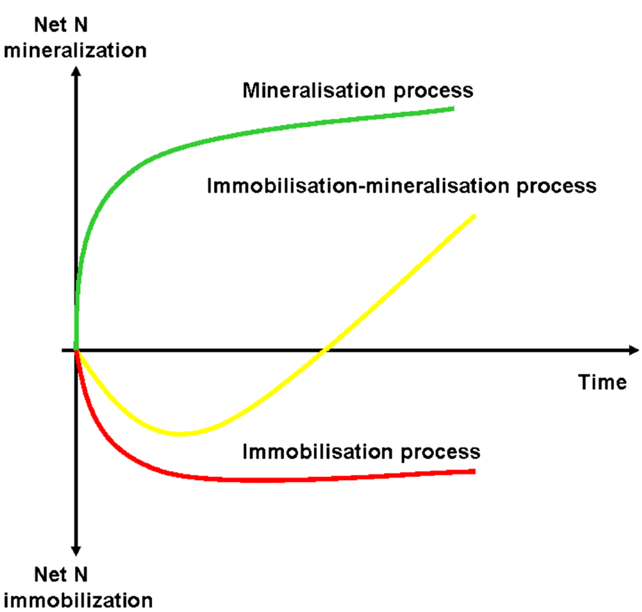

Fig. 3 Sketch of three different process types regarding the effects of returning plant residues on soil inorganic nitrogen over the limited experimental period. Net N mineralisation indicates that surplus inorganic nitrogen occurs in after plant residues are returned to the soil relative to the blank soil. Net N immobilisation indicates that the inorganic nitrogen concentration after returning plant residues to the soil is less than in the blank soil

$$M = D(r_L - r_{CR}) \quad (4)$$

$$D = R_B/(1-e) \quad (5)$$

$$r_{CR} = e \cdot r_B \quad (6)$$

$$M = \frac{R_B}{(1-e)}(r_L - e \cdot r_B) \quad (7)$$

Formula (5) was created from formulas (4) through (6), where M is net nitrogen mineralisation, D is the litter carbon decomposition rate, r_L is the total N:C ratio of the plant residue in the litterbag, r_{CR} is the critical N:C ratio, R_B is the plant residue C that is lost through respiration, r_B is the biomass N:C ratio of the decomposer and e is the carbon use efficiency of the decomposer.

Thus, the maximum of the N release curve corresponds to the critical litter N concentration (r_{CR}), which can be expressed analytically in terms of the N:C ratio as a function of the characteristics of the decomposer ($r_{CR}=e \cdot r_B$) (Manzoni and Porporato 2007). Therefore, when $r_{CR}<r_{L,0}$, net mineralisation occurs at the beginning of decomposition and mineralisation process occurs in the soils with returned plant residues.

Regarding the value of carbon utilization efficiency of the decomposer, strong variations may occur that depend on environmental factors, substrate type (nutritional, elemental composition as well as energy content) and on biochemical degradation and assimilation pathways (Manzoni et al. 2012). However, r_B does not vary systematically along gradients of organic matter and litter N:C ratios and typically remains between 0.07 and 0.2 with an average value of 0.1 (Manzoni et al. 2008).

Thus, it is important to determine the value of carbon utilization efficiency for different ecosystems to determine which pattern exists in a soil with plant residue. In addition, these methods and the influence factors of carbon utilization efficiency are summarised by Manzoni et al. (2012).

The occurrence of mineralisation is a distinguishing standard for immobilisation–mineralisation process and immobilisation process. Theoretically, all plant residues will cause net mineralisation if the experimental period is long enough. However, limited crop growth periods may not provide a long enough period. C:N ratio is an important property of plant residues in the previous researches. A lot of pioneering work on residues decomposition rate index to the C:N ration of residues was done by Martin Alexander in the 1980s (Stroo and Alexander 1986; Alexander 1985).

Several studies (Table 3) have determined empirical critical C:N ratio values for net immobilisation and mineralisation that are helpful for distinguishing the immobilisation process from the mineralisation process and immobilisation process. The critical C:N ratio ranges from 24 to 44, which suggests that the C:N ratio of plant residues that cause immobilisation process should be greater than 44.

3.2 Quantitative prediction of different inorganic nitrogen pattern changes

The effects of returning plant residues to soils on inorganic soil nitrogen are determined based on plant residue properties and soil factors (Heal et al. 1997; Khalil et al. 2005).

For many years, the C:N ratio or the C:N:polyphenol ratio was considered as the most important indicator for predicting N mineralisation during plant residue decomposition (Taylor et al. 1989; Thomas and Asakawa 1993). The C:N ratio of plant residues is a determinant for identifying the extent of inorganic nitrogen immobilisation (as shown in 2.1). In addition, polyphenols can form complexes with proteins, which render them inaccessible to microorganisms and slow down N mineralisation during the early stages of decomposition (Mafongoya et al. 1998; Mutabaruka et al. 2007).

Although the C:N ratio is a useful index, the results that are predicted based on the C:N ratio are not always correct. This is because different components of C and N have different stabilities. Hadas et al. (2004) found that the N recovery from tobacco residues was greater, which potentially resulted from the larger fraction C in the lignin-like pool although the gross N mineralisation of tobacco and rape residues were similar. They also found that the N in rice hulls and in corn and wheat residues was dominantly recalcitrant. However, the rice hulls did not result in N deficiency because most of their C was also recalcitrant. Thus, these authors divided the total C and N into soluble, cellulose-like and lignin-like fractions.

Besides plant residue properties, several soil factors were gradually considered in new models (Khalil et al. 2005). However, these factors have not been thoroughly studied. Previously, many models, e.g. CENTURY model, DAISY model, were established that only used plant residue C:N ratios (Paustian et al. 1997; Magid et al. 1997). Here, we introduced quantitative prediction methods that were based on more detailed indexes of plant residue properties and soil factors.

3.2.1 Predictions based on the integrated indexes

Indexes that integrate plant residue properties and the soil factors can be used to predict soil inorganic nitrogen changes due to plant residues. These integrated indexes, including plant residue quality index, plant residue quality index-modified and organic matter quality index, were gradually developed by researchers based on their correlations with soil inorganic nitrogen concentrations and can be used to predict different process types of changing inorganic nitrogen concentrations.

The plant residue quality index (PRQI) was developed by Tian et al. (1995) to evaluate the agronomic value of different plant residues. The C:N ratio and the lignin and polyphenol concentrations are important descriptors of plant residue quality. Therefore, these descriptors are defined by formula 8:

$$\mathrm{PRQI} = \left[1/(a\,\mathrm{C:N} + b\,\mathrm{lignin} + c\,\mathrm{polyphenols})\right] \times 100 \qquad (8)$$

Based on the coefficient between plant residues C:N, lignin, polyphenols and mean decomposition rate constants, the values of a, b and c were assigned as 0.423, 0.439 and 0.138, respectively.

The PRQI was correlated with the plant residue decomposition rate, soil microclimate, soil fauna density and maize crop performance in the field. The soil moisture and termite density increased as the PRQI values decreased. In addition, the soil temperature, the ant density and the decomposition

Table 3 The empirical critical C:N ratio values of the plant residues between net N mineralisation and net N immobilisation

Incubation environment	Incubation period	Critical C:N ratio	Reference
Laboratory	3–4 months	44	De Neve and Hofman 1996
Laboratory	120 days	36.6	Chaves et al. 2004
Laboratory	11 weeks	40	Vigil and Kissel 1991
Field	>100 days		
Laboratory	168 days	24	Trinsoutrot et al. 2000

rate constants of the plant residues increased as the PRQI values increased.

Although the PRQI provided a method for assessing the agronomic value of plant residues, it has not been related to N dynamics. Therefore, Kumar and Goh (2003) proposed using the plant residue quality index-modified (PRQIM) model to relate the PRQI to changes in soil inorganic nitrogen. Three parameters are used in the PRQIM model, including the C:N, lignin:N and polyphenol:N ratios. The resulting equation is provided as formula 9:

$$\mathrm{PRQIM} = \left[1/(0.526\ \mathrm{C:N} + 0.349\ \mathrm{lignin:N} + 0.125\ \mathrm{polyphenol:N})\right] \times 100 \quad (9)$$

The object of this study was to understand nitrogen release from plant residues. However, this study also measured the changing soil inorganic nitrogen concentrations of the soil with and without residues. According to a correlation test, the changing soil inorganic nitrogen concentrations were significantly correlated with PRQIM. This significant correlation occurred for the data that were obtained within this experiment and for independent data sets that were obtained from the literature.

Khalil et al. (2005) proposed the organic matter quality index (OMQI) to predict the decomposition rate, net N mineralisation and nitrification in different soil types under aerobic conditions. In their report, the net N mineralisation and nitrification were estimated by subtracting the accumulated mineral N ($NH_4^+{-}N{+}NO_3^-{-}N$) and $NO_3^-{-}N$ at day 90 from that at day 0. This index was used to determine the effects of the inherent soil and biochemical properties of the added organic materials on the N transformation processes. In addition, this index was used as a replacement for indicators that are difficult to measure in PRQI and PRQIM. The OMQI uses two parameters, including pH and the C:N ratio (Eq. 10). The OMQI fit the decomposition rate constants well (61 %) with a corresponding prediction level of 67 % when the soil property of 1/CEC(CEC, cation exchange capacity) was included (Eq. 11).

$$\mathrm{OMQI} = \left[1/(0.880\,\mathrm{pH} + 0.120\ \mathrm{C:N})\right] \times 100 \quad (10)$$

$$\mathrm{OMQI} = \left[1/\left(0.686\ \mathrm{pH} + 0.093\ \mathrm{C:N} + 0.221 \times 1/\mathrm{CEC}\right)\right] \times 100 \quad (11)$$

The OMQI was significantly correlated with the decomposition rate constant, net mineralisation and nitrification in the soils that were treated with organic materials with or without the consideration of soil factors. The focus of the OMQI study was soil nitrogen mineralisation and nitrification in plant residues that were returned to the soil. Thus, to predict inorganic nitrogen changes due to plant residues, the soil inorganic nitrogen in the soils without added plant residues should be subtracted.

3.2.2 Predictions based on the first-order kinetic model

Although PRQIM and OMQI can predict net nitrogen mineralisation based on the quality of plant residues, they cannot predict changes in nitrogen mineralisation with time. However, prediction models based on the first-order kinetic model can solve this problem. The N mineralisation of plant residues as a function of time can often be described by the following first-order kinetics model: $AN(t)=AN[1-\exp(-kt)]$, where AN is the amount of mineralisable N, and k is the rate constant. Similarly, the N mineralisation of plant residues can be measured as the difference between the inorganic nitrogen concentrations in the soils with and without plant residues. Therefore, the N mineralisation from the plant residues is equal to the inorganic nitrogen change that results from the plant residues.

De Neve and Hofman (1996) observed that the amount of mineralisable organic N was correlated with the chemical composition rather than the concentration of mineralisable total N. In addition, these authors found that the amount of mineralisable organic N was best correlated with the C:N ratio of lignin. Based on several N mineralisation measurements over a period of 3 to 4 months, these authors fixed the first-order kinetics model to a new group of formulas as follows:

$$\mathrm{N}(t) = \mathrm{N_{min}} + \mathrm{N_{org}}(t)\cdot\frac{\mathrm{N_{org}}}{100} \quad (12)$$

$$\mathrm{N_{org}}(t) = \left(76.6\text{-}0.653\ \text{C-to-N}_{\mathrm{lignin}}\right) \times \left(1\text{-}e^{-\left(1.73\text{-}0.0144\ \mathrm{N_{org}}\right)\times t}\right) \quad (13)$$

In formulas (12) and (13), $N(t)$ represents the inorganic nitrogen change that results from the plant residues at time t, N_{min} represents the initial mineral N concentration in the plant residue and expressed as a percentage of total N. $N_{org}(t)$ represents the percentage of organic N that is mineralised at time t. C-to-N_{lignin} represents the C:N ratio of the lignin fraction. N_{org} represents the organic N concentration in the plant residues and expressed as a percentage of total N. Compared to the disadvantage of PRQIM and OMQI in predicting nitrogen mineralisation changing with time, this model can be used to calculate the concentration of mineralised N at any specific time after incorporating the residues under the experimental conditions.

Similarly, Chaves et al. (2004) observed that the amount of mineralised N (AN) was best correlated with the C:N ratio (R=−0.86) and that the rate constant k was best correlated with the lignin:N ratio (R=−0.94). The resulting formula was expressed as follows: $AN(t)=[-2.03C{:}N+74.2]\times[1-\exp(-(2.93(L{:}N)^{-1.21})t)]$. AN($t$) represents the amount of N mineralised at time t. C:N is the overall C:N ratio of the crop residue. L:N is the ratio of lignin to the total N concentration. In this formula, C:N ration of crop residue is conveniently to be measured, but L:N ration is a more expensive measurement and will require a specialized test.

Formulas that are based on first-order kinetic models may be more effective for assessing inorganic nitrogen changes with time. However, existing research is too limited for obtaining a universal curve. Moreover, the influencing factors, e.g. the plant residue placement, soil environment and ploughing and fertiliser timing, should be considered when establishing new curves.

In conclusion, three different changing inorganic nitrogen progress types may result from plant residues: mineralisation progress, immobilisation–mineralisation progress and immobilisation progress. The mineralisation pattern and immobilisation–mineralisation pattern can be distinguished clearly. However, immobilisation–mineralisation process and immobilisation process are only separated based on the empirical C:N value of the plant residues. Several models (as shown in 3.2) are helpful for improving the accuracy of the distinguishing standards when more plant residue properties and soil factors are considered. In addition, those models can quantitatively predict inorganic nitrogen changes. However, models with greater adaptability and accuracy will likely be established in the future.

4 Synchronism between the soil inorganic nitrogen change patterns and crop nitrogen uptake

4.1 Qualitative evaluation

The rates of average nitrogen accumulation for different crops that including wheat, rice, corn and soybean are presented in Fig. 4. Between 77 and 81 % of the nitrogen was accumulated by rice, corn and soybean between 25 to 34 and 85 to 94 days, i.e. vegetative growth stage. In addition, less than 3 % of the nitrogen was accumulated between 0 and 25 to 34 days, i.e. seedling stage. Finally, 17 to 20 % of nitrogen was accumulated during the reproductive growth stage. Wheat, as an overwintering crop, accumulates 6 % of nitrogen during its seedling stage (0–30 days), 72 % during its vegetative growth stage (30–160 days) and 22 % during its reproductive growth stage (160–230 days). Generally,

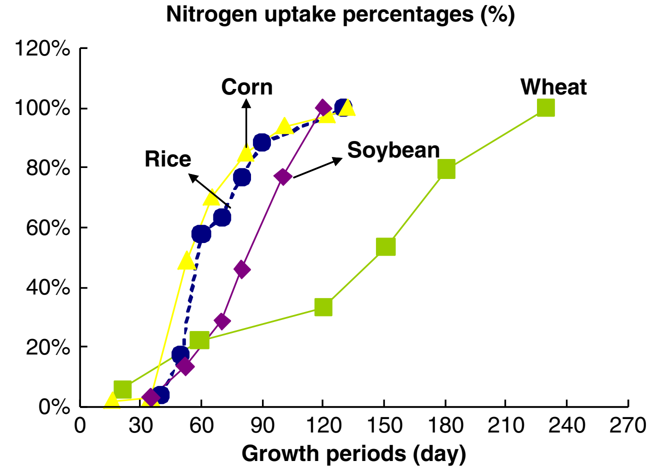

Fig. 4 Nitrogen uptake percentages for the different growth stages of wheat (Cui and Wu 2000; Zhao and Yu 2006), rice (Zou et al. 2002), corn (Zhai 2006) and soybean (Wang et al. 2004). These four staple crops absorb approximately 70–80 % of their nitrogen during their vegetative growth stage and only a small proportion during their seedling stage

crops absorb approximately 70–80 % of their nitrogen during the vegetative growth stage and only a small proportion during their seedling stage. If not enough nitrogen is available in soil with returned plant residues during the soil vegetative growth stage, the yield will be reduced. Conversely, if excessive nitrogen is available during the seedling stage, nitrogen loss may occur.

When the synchronism of the immobilisation–remineralisation process and the crop nitrogen demand pattern are low, plant nitrogen assimilation is negatively affected. Ichir and Ismaili (2002) observed that returning lower-quality plant residue (wheat straw) to the soil resulted in a 5-month N immobilisation process at a depth of 0–15 cm. In addition, soil inorganic nitrogen decreased to 61.6, 46.4 and 30.0 mg kg^{-1} occurred for plant residues that were returned at seeding, at 15 and at 30 days before seeding, respectively. Consequently, the dry matter yield and N accumulation in the wheat crop decreased. In addition to cereal crop residues, Francis (1995) observed the incorporation of residues from cover crops into soils. These authors found that the yield in the following spring wheat crop decreased by 20–30 % due to extensive net N immobilisation during residue decomposition. In addition, grain N uptake and crop yield were also reduced by N immobilisation when crop straw was retained on the surface (Soon and Lupwayi 2012). However, this effect may change with different crop species. Thomsen and Christensen (1998) reported that lower-quality plant residues incorporation reduced the yield and N uptake of the first barley test crop. However, the sugar beet yields were unaffected by straw, likely due to their longer growth period. Hemwong et al. (2008) reported that incorporating lower-quality plant residues (sugarcane straw) residue did not significantly affect the growth of legumes due to their N_2 fixation capacities.

However, the synchronism can be enhanced by high-quality plant residues. For example, Trinsoutrot et al. (2000)

observed that residues with low N concentrations induced net N immobilisation after 168 days (−22 to −14 mg N g^{-1} of added C), but residues with high N concentrations induced little net immobilisation or mineralisation (−3 to +4 mg N g^{-1} of added C). In addition, Kumar and Goh (2002) reported that the grain yield and N uptake of a wheat crop was significantly greater following the return of leguminous residues rather than non-leguminous residues. These authors also indicated that the grain yield of the wheat crop was significantly correlated with the C:N ratio of the residues. Gentile et al. (2009) showed that *Tithonia* residues treatment resulted in an early season N release of 22 kg N ha^{-1} in the upper 30 cm of the soil profile. However, the maize residues treatment resulted in an immobilisation of 34 kg N ha^{-1} after N fertiliser application.

In addition, different plant parts have different influences due to their different chemical properties. Chaves et al. (2004) reported that green manure leaves release more N than stems and roots. In addition, Thomsen (1993) reported that plant shoots contribute more nitrogen than roots for plant growth. This result was potentially caused by the different lignin concentrations of the residues, which corresponded to N immobilisation (Dossa et al. 2009).

The inorganic nitrogen changing, which is induced by different plant residues, may affect nitrogen losses differently. Plant residue applications can enhance the role of soil microbes as a temporal N source or sink, which results in the conservation of potentially leachable N until a later crop growth phase, especially in years with relatively severe N leaching (Sugihara et al. 2012). As N deficiencies can be caused by low-quality residue at the early stage of decomposition (Myers et al.,1994), N loss risk through leaching also can be reduced (Gentile et al.,2009). However, for high-quality residues, Thomsen and Christensen (1998) observed that sugar beet tops enhanced N leaching during two winter experimental periods. These results suggested that the effects of plant residues on nitrogen leaching are different for different residue qualities. Generally, the residues qualities are related to the plant residues N contents, C:N ration, lignin contents and so on.

In conclusion, the soils that followed mineralisation process generally promoted nitrogen uptake and resulted in greater yields and a higher risk of nitrogen loss. Although net immobilisation occurred throughout immobilisation–mineralisation process and immobilisation process, the uptake of nitrogen by the crops was not necessarily reduced. Instead, the results depend on the synchronism between the changing soil inorganic nitrogen and the crop nitrogen uptake.

4.2 Synchronism index

Although the effects of plant residues on soil inorganic nitrogen concentrations have been thoroughly studied, the influences of plant residues on crop nitrogen uptake have not been quantified. Therefore, we propose a conceptual synchronism index (SI) for assessing the synchronism between changing soil inorganic nitrogen concentrations in plant residues that are returned to the soil and crop nitrogen uptake (formula 14). In formula 14, SIN(t) represents the soil inorganic nitrogen concentration in the root layer during the growth period t. AE[t, SIN(t)] represents the crop inorganic nitrogen assimilation efficiency during growth period t and at a soil inorganic nitrogen concentration of SIN(t). For plant nitrogen accumulation at time t, i.e. PN(t)(formula 15), we expressed it as the plant nitrogen amount at time t, and C(t) is the plant nitrogen content at time t, M(t) is the plant weight. The SIN(t) (formula 16) is expressed in three parts as follows: the inorganic nitrogen from the fertiliser (FN), the inorganic nitrogen from soil mineralisation in the absence of returned plan residues [SNM(t)], and the inorganic nitrogen change that results from returning plant residues to the soil [RE(t)]. Because the temporal variations of the inorganic nitrogen changes can be expressed by first-order kinetics, first-order kinetics were used to express the SNM(t) and RE(t) (formulas 17 and 18). In formula 17, N_0 represents the soil mineralisable organic nitrogen, and m represents the rate constant. In formula 18, AN represents the amount of mineralisable N in the plant residue and k represents the rate constant. For RE(t), related studies have been based on laboratory data. However, additional studies based on the field data are expected to evaluate the synchronism. Research regarding the AE[t, SIN(t)] remains limited. However, the importance of AE[t, SIN(t)] for soil nitrogen management may be established gradually.

$$\mathrm{SI} = \int_0^T [\mathrm{SIN}(t)\cdot AE(t, SN(t)) - \mathrm{PN}(t)] \tag{14}$$

$$\mathrm{PN}(t) = \mathrm{C}(t)\cdot\mathrm{M}(t) \tag{15}$$

$$\mathrm{SIN}(t) = \mathrm{FN} + \mathrm{SNM}(t) + \mathrm{RE}(t) \tag{16}$$

$$\mathrm{SNM}(t) = \mathrm{N}_0(1 - e^{-\mathrm{m}t}) \tag{17}$$

$$\mathrm{RE}(t) = \mathrm{AN}[1\text{-}\exp(\text{-}kt)] \tag{18}$$

Based on the synchronism index, once the plant N nutritional demand is satisfied, any residual N in soil beyond this demand is subject to loss.

5 Adjustment measures

5.1 Mineralisation process

Regarding the plant residues that cause mineralisation process in soils, the objective of the adjustment measures is mainly to control inorganic nitrogen losses. Immobiliser and materials for remineralisation were used to adjust mineralisation process.

De Neve et al. (2004) used compost with a high C:N ratio, straw and compost with a low C:N ratio as immobilisers and molasses for remineralisation to synchronise the residue N availability with the crop N demand. In this study, the addition of molasses resulted in strong and significant remineralisation which equivalent to 73 % of the initially immobilised N during the second stage in the high C:N ratio compost treatment. Chaves et al. (2006) used straw as an immobiliser and vinasses (distillation residue in wine industry) for remineralisation to control nitrogen losses from celery residue. This research indicated that the addition of vinasses increased the concentration of remineralised celery-^{15}N relative to the straw treatment without vinasses by 6.9 % of celery derived ^{15}N.

Chaves et al. (2005) indicated that stimulating remineralisation of immobilised N is not easy. The slow progress towards the breaking point of net N mineralisation and net N immobilisation indicated that only 12 to 48 % of the immobilised ^{15}N was remineralised within 2 years after straw incorporation (Thomsen and Christensen. 1998). In this case, the tannic acid and phenolic lignin from the residues potentially cause the nitrogen to become unavailable through covalent binding (Olk et al. 2006; De Neve et al. 2004).

Thus, the immobilizer can effectively reduce N losses, but immobilized N cannot be effectively released, in the short-term, by re-mineralization to satisfy plant N nutritional demands.

5.2 Immobilisation–mineralisation process and immobilisation process

The risk of nitrogen loss is reduced by plant residues that cause immobilisation–mineralisation process and immobilisation process in soils. Therefore, the object of the adjustment measures was to reduce the nitrogen immobilisation that results from these plant residues.

5.2.1 Ploughing and fertiliser application timing

Fertiliser nitrogen is an important inorganic soil nitrogen source. The timing of ploughing and fertiliser application affect the immobilisation of fertiliser nitrogen in monoculture farmland.

Ploughing in monoculture farmland should be done in the autumn to avoid serious nitrogen immobilisation during the plant growth period. Carefoot et al. (1994) observed that total plant N concentrations were reduced following spring ploughing rather than autumn ploughing when straw was incorporated. In addition, autumn ploughing with straw incorporation did not decrease the total plant N concentration relative to absence of straw.

To enhance the fertiliser nitrogen use efficiency and to avoid large amounts of fertiliser nitrogen immobilisation, fertiliser nitrogen should be applied after plant residues are returned. Carefoot and Janzen (1997) observed that plant N was derived from fertiliser exhibited a significant interaction between the timing of straw-tillage and fertiliser application. When straw was incorporated in the fall, the plant N concentrations that were derived from the fertiliser were 44.0 kg N ha^{-1} for spring-applied N and 30.6 kg N ha^{-1} for fall-applied N. Olk et al. (2006) reported that the fertiliser N recovery was lower for the fall-applied N relative to the spring-applied N. This result likely occurred due to decreased immobilisation. According to Rosell et al. (1992), the total areal plant dry matter was lowest (4.94 Mg ha^{-1}) when N was added at the beginning of the fallow period, which indicated strong N immobilisation. In addition, the highest areal plant dry matter (8.30 Mg ha^{-1}) occurred when N was incorporated during seeding.

Overall, for the plant residues that cause immobilisation–mineralisation process and immobilisation process, the fallow period should be long enough for the plant residues to begin decomposition before seeding. In addition, fertilising after the fallow period can reduce the immobilisation of inorganic nitrogen during the crop growth period.

5.2.2 The locations of the returned plant residues (mulching or incorporated into soil)

Generally, the decay rates of the residues that were placed on the soil surface are slower than when the residues are incorporated into the soil. In fact, surface-placed residues only decay rapidly when the moisture, nutrient status and soil fauna activity are not limiting (Mando and Stroosnijder 1999; Mando et al. 1999). Coppens et al. (2007) indicated that the decomposition rate of straw depends on the residue location. For example, residue on the surface results in a decomposition rate that is approximately 35 % less than the decomposition rate of incorporated residues. Due to the slow decomposition of surface-applied plant residues, the net release of N is delayed (Bradford and Peterson 2000). Plant residues that caused immobilisation–mineralisation process or immobilization process in soils cannot prevent the immobilisation of inorganic N due to their high C:N ratios (Bird et al. 2001). However, the extent of immobilisation of surface applied plant residues is lower than for incorporated plant residues. Thus, net N mineralisation is always higher in plant residue mulch treatments relative to incorporation treatments (Coppens et al. 2007).

Despite the improved net N mineralisation, the grain yield under the mulched treatment was significantly lower than under other management treatments due the lower established plant population (Kumar and Goh 2002). Leaving plant residues on the soil surface creates a cooler and wetter environment than incorporation of plant residues into the soil. In addition, by modelling the gross N mineralisation and immobilisation, leaving the plant residues on the soil surface increased the risk of nitrate leaching relative to residue incorporation (Coppens et al. 2007). Therefore, the extent of nitrogen immobilisation can be reduced by changing the placement of the plant residue. However, the seeding and nitrogen loss problems must be solved when applying plant residues on the soil surface.

6 Conclusions

When plant residues are returned to the soil, they can cause soil inorganic nitrogen changes through biotic immobilisation–remineralisation, abiotic immobilisation, soil organic nitrogen mineralisation, and plant residue organic nitrogen mineralisation. Depending on the occurrence of net immobilisation and its duration within the limited experimental period, the inorganic nitrogen changes process that resulted from the plant residues were divided into three different types. Mineralisation process and immobilisation–mineralisation process can be distinguished based on formulas. However, immobilisation–mineralisation process and immobilisation process can only be distinguished based on empirical plant residue C:N values. To predict inorganic nitrogen changes quantitatively, integrated indexes that contain different forms of plant residue carbon and nitrogen and soil properties are more effective than indexes that rely on the C:N ratio of plant residues. However, research remains limited for obtaining a universal curve.

Soils with mineralisation process usually promote crop nitrogen uptake, increased yields, and a greater risk of nitrogen loss. Net immobilisation occurs throughout immobilisation–mineralisation process and immobilisation process. However, this immobilisation does not indicate that the uptake of nitrogen by crops will be reduced. In addition, the results depend on the synchronism between the soil inorganic nitrogen change and the crop nitrogen uptake. The conceptual synchronism index was established to evaluate this synchronism. Finally, several measures can be used to adjust the synchronism. As research becomes more advanced, additional methods may be identified that will allow the return of plant residues to soils to become an efficient method for improving farmland nitrogen dynamics.

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