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The effect of plastic mulch on the fate of urea-N in rain-fed maize production in a semiarid environment as assessed by ^{15}N-labeling

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ABSTRACT

A better understanding of the fate of fertilizer nitrogen (N) is critical to design appropriate N management strategies in plastic-mulched croplands. We evaluated the effects of plastic mulch on urea-N recovery by crops and loss from soil in furrow-ridge plots, with and without maize (*Zea mays* L.) cropping, in a semi-arid rain-fed site in China. We applied the same rate of urea-N (281 kg ha^{-1}) to all treatments during the preparation of the furrow-ridges in 2011 and 2012 but ^{15}N-labeled the urea in 2011 only. We used transparent film to cover all soil surfaces in the mulched treatments and seeded maize in furrows in treatments with crop. In 2011, plastic mulch increased the total N uptake in the aboveground biomass of maize by 53%, whereas it decreased the in-season labeled-N uptake by 19%, compared to non-mulched treatment. At harvest in 2011, in mulched treatments the total labeled-N remaining in the 0–170 cm soil layer was 25% greater whereas unaccounted labeled-N was 69% less, than in non-mulched treatments, regardless of whether maize was cropped. In 2012 the effect of mulch on total maize N uptake was comparable to that in 2011, but the residual soil labeled-N uptake by maize was 63% higher in mulched compared to non-mulched treatment. At harvest in 2012, plastic mulch increased total labeled-N remaining in the 0–170 cm depth in cropped soils and unaccounted labeled-N in non-cropped soils, compared with no mulch. Our results indicate that plastic mulch profoundly changes the fate of urea-N in maize production in cold and dry croplands.

1. Introduction

Plastic mulch is used worldwide in vegetable and grain production. In China, it has contributed greatly to increased food production since the 1970s (Deng et al., 2006). Recently, by combining with a ridge–furrow approach, plastic mulch has especially helped augment maize (*Zea mays* L.) production in temperature and rainfall limited areas (Gan et al., 2013; Chai et al., 2014). The plastic film fully-mulched ridge–furrow cropping method significantly increased the productivity of croplands by efficiently conserving water in the soil (Liu et al., 2014a; Jiang and Li, 2015) and increasing the soil temperature (Hai et al., 2015).

In any cropping system, nitrogen (N) management determines, to a large extent, the yield and quality of products, their costs and environmental impacts. To design an optimal N management strategy, a better understanding of the fate of applied fertilizers is of vital importance. As a physical barrier, plastic mulch influences the exchanges of matter and energy between the soil and atmosphere and thus changes the hydrothermal conditions of the soil. As a result, plastic mulch may alter the behavior of fertilizer N in the plant–soil system and the N management strategy should be different from the non-mulched cropping system. However, the effects of plastic mulch on the fate of fertilizer N have been seldom studied (Kettering et al., 2013), especially in grain production of semiarid areas.

The present study is part of a larger experiment (hereafter referred to as the 'main experiment') which examined the interactive effects of plastic mulch and the presence of a crop on soil moisture dynamics, water balance and N mineralization (Liu et al., 2014a; Hai et al., 2015). The main experiment and present study were performed continuously in a ridge–furrow prepared field during the cropping seasons in 2011 and 2012. We reported that without maize, plastic mulch increased daytime soil temperature by about 3.0 °C in the 0–15 cm layer throughout the season, whereas in the presence of maize plastic mulch increased daytime soil temperature by about 2.8 °C, but only in the seedling and elongation stages (Hai et al., 2015). In mulched treatments, soil moisture

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and downward water flow significantly increased compared with in non-mulched treatments over the soil profile due to the blocked soil water evaporation (Liu et al., 2014a). The objectives of the present study were to study the effects of plastic mulch on maize fertilizer N recovery and losses of fertilizer N in ridge–furrow plots. We hypothesized that plastic mulch would increase the fertilizer N recovery by maize. This is because improving soil temperature and moisture, plastic mulch significantly augments maize grain yield and biomass production, and thus total N uptake (Hai et al., 2015). We also hypothesized that plastic mulch would affect fertilizer N loss from the soil because mulch-induced changes in the soil temperature and water conditions would directly or indirectly influence the physical and/or biochemical pathways of N loss from the soil.

2. Materials and methods

2.1. Study site

The study site was located in Yuzhong County, Gansu Province, China (35°54′N, 104°05′E; 2013 m asl). The nearest weather station (about 10 km away) recorded a mean annual temperature of 6.6 °C and precipitation of 382 mm. The measured rainfall amount during maize growth at the site was 284 and 391 mm in 2011 and 2012, respectively. The experiment was performed on a flat field, in which the soil developed from loess, classified as Ustorthents according to U.S. soil taxonomy (Soil Survey Staff, 1975). Before fertilization in 2011, in the top 15 cm, the soil contained 9.8 g organic carbon kg^{-1}, 1.0 g total N kg^{-1}, 24 mg mineral N (total as $NH_4{}^+$–N and $NO_3{}^-$–N) kg^{-1} and 14 mg Olsen P kg^{-1}; the soil pH was 8.4 (soil:water, 2.5:1). The soil bulk density ranged from 1.08 to 1.33 Mg m^{-3} and the soil was of a silt loam texture in depths of 0–170 cm.

2.2. Main experiment design

In the main experiment, four treatments were replicated three times in a randomized complete block design (Liu et al., 2014a; Hai et al., 2015). The four treatments were: (1) no mulch and no crop (control); (2) mulch and no crop (bare soil covered by plastic mulch); (3) no mulch with maize; and (4) mulch and maize together. The ridge–furrow cropping pattern comprised of alternating narrow (15 cm high × 40 cm wide) and wide (10 cm high × 70 cm wide) ridges (Fig. 1). Each of the 12 plots was 39.6 m^2 (6.6 × 6 m). Within each of those 12 plots (hereafter referred to as the "main plots"), one micro plot was established to monitor the fate of N from applied urea for the present study, by using ^{15}N-labeling technique, described further below (^{15}N labeling study) (Fig. 1).

The main experiment was set up 18 days prior to sowing on 27th April 2011. Each main plot was treated with 276 kg N ha^{-1} as urea granules and 40 kg soluble P ha^{-1} as superphosphate powder after soil sampling and before ridge–furrow shaping; this fertilization regime is recommended for maize crops in areas by the Gansu Agricultural Extension Station. Immediately after preparation of the ridge–furrows by a man-powered device in all treatments, the whole land surface (all ridges and furrows) was covered with polyethylene film (colorless and transparent, each strip was 0.008 mm thick and 1.2 m wide) for the mulched treatments (mulch; mulch + maize) (Fig. 1; also see pictures published by Hai et al., 2015). Perforations (around 1 cm in diameter and 20 cm apart) were then drilled through the film in the furrows using a handheld device (Chai et al., 2014). These perforations helped collect rainwater from the ridges and enter the root zone. For the cropped treatments, one row of maize (cv. hybrid Jiudan 4) was seeded in each furrow at a spacing of 35 cm (Liu et al., 2014a; Hai et al., 2015), to produce a density of 52,500 plants ha^{-1} as used in local

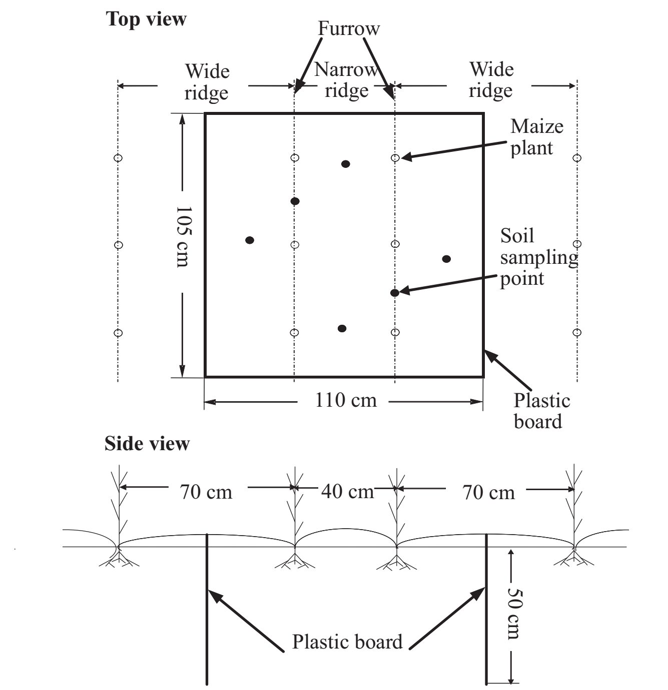

Fig. 1. Top and side views of the ridge–furrow maize cropping pattern, micro plot design (enclosed by four plastic boards) and soil sampling scheme. The wide ridges were 10 cm high, whilst the narrow ridges were 15 cm high. Maize was seeded in the furrows.

farmlands. The same handheld device as that used to puncture holes in the film was used for seeding. After harvest in early October, the aboveground parts of the maize were manually removed from the main plots in the cropped treatments and the plastic mulch was left in the main plots of the mulch treatments.

In 2012, the old plastic mulch from 2011 was removed from the mulch treatments and all 12 main plots were ploughed to a depth of 15 cm by using spades, three weeks prior to sowing on 27th April. Soils were sampled and urea and superphosphate were applied, at the same rates as in 2011, then the ridge–furrow system was reshaped for all 12 main plots. Plastic mulch was immediately applied again for the mulch treatments, as per 2011. The maize cultivar, row spacing, and density in the main plots were all the same as in 2011 for the cropped treatments. The maize was harvested in late September.

2.3. ^{15}N labeling study design

For the ^{15}N labeling study, in 2011 a rectangular micro plot (110 cm × 105 cm; 1.155 m^2) was established in the upper right corner of each of the main plots (145 cm from the sides of the main plot) (Fig. 1), before the main plots were treated with fertilizers. Each intact micro plot was enclosed tightly by four plastic boards (1 cm thick) to a depth of 50 cm. The soil within each micro plot was carefully protected from contamination by N fertilization of the main plots. Within each micro plot, 69.3 g of ^{15}N-labeled urea granules (containing 46.83% N with 10.22% ^{15}N abundance), equivalent to 281 kg N ha^{-1} (as similar as the main plot application rate) was spread on the soil surface. Then the ridge–furrows were manually modeled into the micro plots, corresponding to the main plots. The whole surface of each micro plot was then covered with polyethylene film for the mulch treatments. Perforations were drilled through the film in the furrows, in the same pattern as in the main plots. After emergence, six seedlings were kept in each micro plot in the cropped treatments (Fig. 1) to match the maize density of the main plots. All aspects (N and P fertilization, soil surface modeling, mulching, maize cultivar and planting density and spacing) in the micro plots fully mimicked those of the respective main plots.

At maturity in 2011, all six maize plants within each micro plot of the cropped treatments were harvested. Grains, cob cores, leaves (including sheaths around cobs and stems) and stems were separately oven-dried at 65 °C to a constant weight. Within each micro plot, soils were sampled from six points using an auger (38 mm inner diameter) at the following depths: 0–15, 15–30, 30–50, 50–70, 70–90, 90–110, 110–130, 130–150, and 150–170 cm (Fig. 1). The subsamples from each respective depth were pooled to produce one composite sample at each depth for each micro plot. From each micro plot of cropped treatments, the roots of the six plants were excavated, down to 30 cm depth, and washed; soil drawn out was carefully returned to the respective micro plot. The roots were oven-dried at 65 °C to a constant weight.

In 2012, prior to seeding within each micro plot, the soil was ploughed using a spade then 69.3 g unlabeled urea was spread (that is, urea was ^{15}N-labeled only in the 2011 cropping season) and the ridge–furrows were reshaped. All other management practices and experimental operations were exactly the same as 2011.

During the two cropping years, weeds that grew in the non-mulched micro plots were pulled out by hand at their early seedling stage, and then returned to the soil surface. In the mulched micro plots, the weeds were left unmanaged, as their growth was suppressed by the plastic mulch. No chemical was used to control diseases or pests.

2.4. ^{15}N labeling study sample analysis

Finely ground grains, cob cores, leaves, stems and roots were digested in concentrated H_2SO_4 and H_2O_2 (Lu, 2000), and the N in the digests was distilled using micro Kjeldahl apparatus. Air-dried soil samples were ground and sieved through a 0.15 mm mesh and total N was determined by a permanganate-reduced iron modification of the Kjeldahl method, to include nitrate and nitrite (Bremner and Mulvaney, 1982). Mineral N in fresh soil samples was extracted with 2 M KCl and distilled using micro Kjeldahl apparatus, in the presence of MgO and Devarda alloy (Keeney and Nelson, 1982). After titration, the distillates of the plant N, total soil N and soil mineral N were condensed under acidic conditions in a water bath to 2–3 mL to allow ^{15}N isotope ratio analysis by a gas isotope mass spectrometer (MAI-271, Thermo Fisher, USA).

2.5. Calculations and statistical analyses

A series of parameters were calculated based on the results of the experiments, including: the fertilizer N uptakes in different plant parts, fertilizer N recovery in the aboveground biomass, the total, mineral and organic labeled-N in each soil layer and across all soil depths, and the unaccounted for labeled-N in 2011 and 2012.

The amount of N in each maize organ and total soil N or soil mineral N in each soil layer was derived from the labeled-urea ($\text{NdfF}_{\text{labeled}}$), calculated as:

$$\text{NdfF}_{\text{labeled}} = \text{N content} \times {}^{15}\text{N atom \% excess}/\ \text{urea}\,{}^{15}\text{N abundance (10.22\%)}$$

The fertilizer N recovery was calculated according to:

$$\text{Fertilizer N recovery (\%)} = (\text{total labeled} - \text{N in the above ground biomass}/\text{labeled} - \text{N applied}) \times 100$$

The organic labeled-N in each soil layer was calculated as the difference between total labeled-N minus the mineral labeled-N in the respective soil layer. The total, mineral and organic labeled-N in the 0–170 cm soil profile was calculated as the sum of the respective N fraction across all soil depths. The unaccounted for labeled-N in the first season (2011) was calculated as the amount of labeled-N applied in 2011 (281 kg ha^{-1}) minus the sum of labeled-N in the whole plant (including root biomass) and in the 0–170 cm soil profile measured. The unaccounted for labeled-N in the second season (2012) was calculated as the difference between the labeled-N in the 0–170 cm soil profile at harvest in 2011 and the sum of labeled-N in the whole plant and in the 0–170 cm soil profile at harvest in 2012.

Differences in the N uptake or fertilizer N recovery by maize between maize-planted treatments were each analyzed using a one-way ANOVA. A two-way ANOVA, with the presence/absence of mulch and maize as the two fixed factors, was applied to evaluate the treatment effects on labeled-N in the soil and unaccounted for labeled-N in the plant–soil system. Before statistical analyses, all data pools were tested for normal distribution and homoscedasticity. All statistics were performed using SPSS 13.0 (SPSS, Chicago, IL) (Xue, 2011). Significant differences between means were identified using the least significant difference (LSD) at $P < 0.05$.

3. Results

3.1. In-season (2011) effects

In 2011, maize grain yield with mulch was 70% higher than that without mulch (Table 1). Leaf, stem, and cob core biomasses were all significantly greater when mulch was used relative to no mulch (Table 1). Corresponding to the larger biomass of the different plant parts, mulch increased N uptake in total aboveground biomass by 53% (Table 1); N concentrations in maize organs were generally lower under no mulch (data not shown).

In the treatment without mulch, about half of the N absorbed in the different aboveground parts of the maize was derived from the soil, and half was from the labeled-urea (Table 1). In contrast, within the treatment with mulch, about three quarters of the N absorbed by the maize in the aboveground parts came from the soil and just one quarter came from the labeled-urea (Table 1). Compared with no mulch, the N derived from the soil in the various aboveground organs more than doubled in the treatment with mulch; however, the amount of N from the labeled-urea was either the same or less (Table 1). The in-season maize fertilizer N recovery in the aboveground biomass for 2011 was 23% without mulch and 18% with mulch; that is to say, when mulch was used fertilizer N recovery decreased by 22% ($P < 0.001$).

Root biomass was 26% higher in the treatment with compared to that without mulch (Table 1). Similar to the aboveground parts of the maize, the N present in the roots at harvest in the treatment with mulch mainly came from the soil (Table 1).

At harvest in 2011, plastic mulch increased total labeled-N in the 0–170 cm soil by 25% relative to no mulch, regardless of whether maize was grown (Table 2). The increased total labeled-N in mulched treatments was mainly ascribed to changes in labeled N in mineral form, which was always higher than in non-mulched treatments (Table 2). This pattern was more prominent in the upper 0–50 cm layer, where, on average, the mineral labeled-N was 98% greater in the treatments with mulch compared to those without, whereas the organic labeled-N was 38% less ($P < 0.001$) (Fig. 2a–d).

The total labeled-N in the 0–170 cm depth was 22% less in the cropped than in the non-cropped treatments, apparently due to the uptake of N by maize (Table 2). The lower total labeled-N in the

Table 1
Maize dry matter biomass, total N uptake, and N derived from soil (NdfS) and labeled-urea fertilizer ($NdfF_{labeled}$) in different organs, as affected by plastic mulch at harvest in 2011.

Plant parts	Treatments	Dry matter (Mg ha^{-1})	Total N uptake (kg ha^{-1})	NdfS (kg ha^{-1})	$NdfF_{labeled}$ (kg ha^{-1})
Grains	Maize	5.32b	79.3b	40.1b	39.2a
	Maize + mulch	9.02a	123.1a	88.8a	34.3a
Leaves	Maize	1.62b	22.7b	11.5b	11.2a
	Maize + mulch	3.57a	32.3a	24.1a	8.2b
Stems	Maize	2.32b	16.2b	7.9b	8.3a
	Maize + mulch	4.81a	27.7a	21.4a	6.3a
Cob cores	Maize	1.68b	9.0b	4.2b	4.8a
	Maize + mulch	2.21a	11.6a	9.0a	2.6a
Aboveground biomass	Maize	10.93b	127.1b	63.6b	63.5a
	Maize + mulch	19.61a	194.6a	143.2a	51.4b
Roots	Maize	0.99b	4.2a	2.1b	2.1a
	Maize + mulch	1.25a	5.9a	4.6a	1.3a

Different letters within a column in each maize organ indicate that the means differ at $P \leq 0.05$ between treatments.

cropped soils was mainly due to lower levels of organic labeled-N, whilst decreasing mineral fraction in the cropped soils occurred only when mulch was not used (Table 2).

In the treatments without mulch, 81–85% of the total labeled-N over the 170 cm soil depth was distributed in the upper 50 cm layer (Fig. 2a and c). However, in the treatments with mulch, 63–67% of the total labeled-N was found in the upper 50 cm layer, thus more labeled-N had moved to soil layers below 50 cm (Fig. 2b and d). The mineral and organic labeled-N contents of the soil were close to zero at and below 100 cm depth in the treatments without mulch, but they were both present until 170 cm soil depth in the treatments with mulch at harvest (Fig. 2a–d).

In the 2011 growing season, plastic mulch decreased the unaccounted for labeled-N by 69% compared to no mulch, regardless of whether maize was grown (Table 2).

To sum up, by the time of maize harvest in 2011, in the absence of maize, 77% of the labeled-N (281 kg ha^{-1}) remained in soil and 23% was lost from soil without mulch; however, 93% stayed in soil and only 7% was missing with mulch (Table 2). In the presence of maize, 23 and 58% of the labeled-N were recovered in the whole maize plant (including root biomass) and soil, respectively, and 19% was lost from soil without mulch, which contrasted with that 19 and 75% was found in the whole plant and soil, respectively, and only 6% was unaccounted with mulch (Table 2).

3.2. After effects (2012 season)

In 2012, the effects of plastic mulch on maize biomass production and N uptake in the various plant parts were comparable with those observed in 2011 (Tables 1 and 3). The residual labeled-N from 2011 recovered in the different maize organs was generally greater in the treatment with mulch compared to that without (Table 3). The labeled-N uptake in the aboveground maize biomass in the treatment with mulch was 63% higher than that in the treatment without mulch (Table 3). The recovery of the labeled fertilizer N (% of labeled-N in the aboveground biomass in 2012 over labeled-N applied in 2011) by the maize crop was 16% with mulch versus 10% in the treatment without mulch.

At the 2012 harvest, maize decreased total labeled-N in the 0–170 cm depth only in non-mulched soils (Table 2). Plastic mulch decreased the total labeled-N without maize but increased the total labeled-N with maize, compared with no mulch (Table 2). Of the total labeled-N, the mineral amount was smaller but the organic form was greater in the mulched soils than in the non-mulched soils (Table 2). This observation was in contrast to the situation at harvest in 2011, where the mineral labeled-N was significantly greater in the mulched soils, while the organic labeled-N in the soil was unaffected by mulch (Table 2).

Table 2
Labeled-N recovered in the whole plant (aboveground plus root biomass), in the 0–170 cm soil layer, and unaccounted for labeled-N in the plant-soil system among different treatments at harvest in 2011 and 2012.

Cropping year	Treatment[a]	Labeled-N in the whole plant[b] (kg ha^{-1})	Labeled-N in soil			Unaccounted for labeled-N (kg ha^{-1})
			Total (kg ha^{-1})	Mineral form (kg ha^{-1})	Organic form (kg ha^{-1})	
2011	Control	0	216.5	86.4	130.1	64.5
	Mulch	0	262.6	133.9	128.7	18.4
	Maize	65.6a	162.0	72.1	89.9	53.4
	Maize + mulch	52.7b	210.6	136.3	74.3	17.7
	Summary of ANOVA[c]					
	Mulch ($LSD_{0.05}$)		***(7.1)	***(5.3)	ns	***(8.5)
	Maize ($LSD_{0.05}$)		***(7.1)	ns	***(8.4)	ns
	Mulch × maize ($LSD_{0.05}$)		ns	*(7.4)	ns	ns
2012	Control	0	145.4	60.1	85.3	71.1
	Mulch	0	134.9	17.7	117.2	127.7
	Maize	28.5b	112.8	37.3	75.5	20.7
	Maize + mulch	45.8a	135.0	7.3	127.7	29.8
	Summary of ANOVA[c]					
	Mulch ($LSD_{0.05}$)		ns	***(1.8)	***(5.0)	***(11.0)
	Maize ($LSD_{0.05}$)		***(5.4)	***(1.8)	ns	***(11.0)
	Mulch× maize ($LSD_{0.05}$)		***(7.6)	***(2.5)	*(7.0)	**(15.5)

* Significant at $P \leq 0.05$; ** significant at $P \leq 0.01$; *** significant at $P \leq 0.001$; ns not significant.
[a] The treatment "control" means "no mulch + no maize cropping".
[b] Different letters indicate that means are different between maize and maize + mulch treatment at $P < 0.05$.
[c] Values in parentheses after asterisks are the least significant difference at $P < 0.05$ ($LSD_{0.05}$).

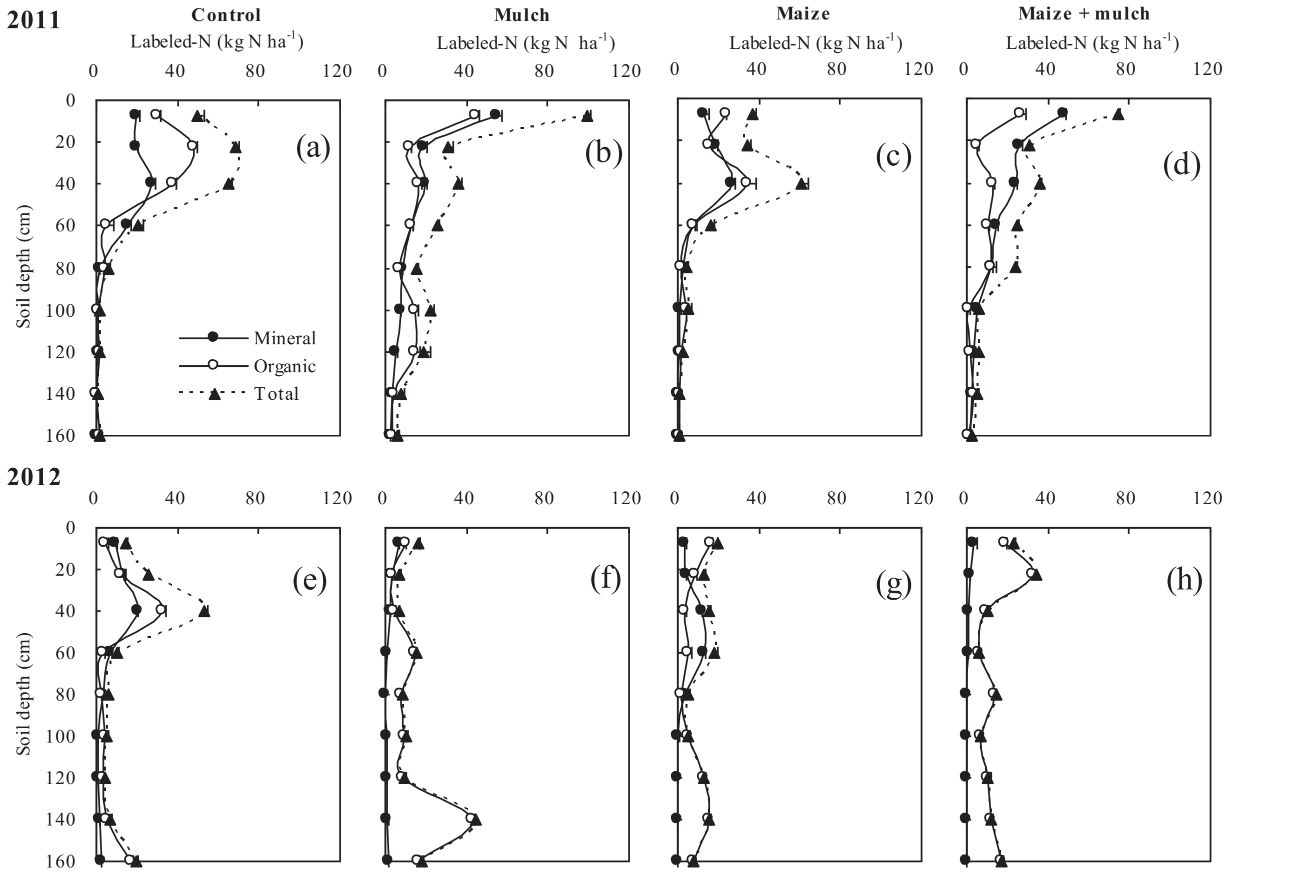

Fig. 2. Profiles of mineral, organic and total labeled-N in the 0–170 cm soil layer of each of four treatments at harvests in 2011 (a–d) and 2012 (e–h): (a) and (e), control (no mulch/no maize); (b) and (f), mulch without maize; (c) and (g), maize without mulch; (d) and (h), maize and mulch treatments. Error bars are standard errors of means (n = 3).

At harvest in 2012, the non-cropped treatments contained the majority of total and organic labeled-N in the upper 50 cm of soil when no mulch was used, but the labeled-N was mostly present in the lower soil profile (120–170 cm depth) when mulch was used (Fig. 2e and f). However, with maize, the total and organic labeled-N was evenly distributed over the whole soil profile, independently of the presence of mulch (Fig. 2g and h).

Between the harvests in 2011 and 2012, mulch increased the loss of labeled-N from soil by 80% in the absence of maize. This contrasted with the situation at harvest in 2011, when the unaccounted for labeled-N was smaller under mulch than under no mulch regardless whether maize was grown (Table 2). Maize decreased the unaccounted for labeled-N by 71–77% compared with no maize (Table 2).

Overall, at harvest in 2012, in the absence of maize, 52% of the labeled-N applied in 2011 (281 kg ha^{-1}) remained and 25% was further unaccounted in the 170 cm soil profile without mulch; however, 48% was maintained and 45% was further not detected in the soil profile with mulch (Table 2). In the presence of maize, 10 and 40% of the labeled-N applied in 2011 were recovered in the whole plant and 170 cm soil profile, respectively, and additional 8% was unaccounted without mulch; however, 16 and 48% were recovered in the whole plant and soil profile, respectively, and additional 11% was not detected with mulch (Table 2).

Table 3
Maize dry matter biomass, total N uptake, N derived from soil (NdfS) and fertilizer (NdfF) in 2012, and N derived from labeled-urea fertilizer in 2011 ($NdfF_{labeled}$), as affected by plastic mulch at harvest in 2012.

Plant parts	Treatments	Dry matter (Mg ha^{-1})	Total N uptake (kg N ha^{-1})	NdfS + NdfF (kg N ha^{-1})	$NdfF_{labeled}$ (kg N ha^{-1})
Grains	Maize	5.89b	84.6b	66.6b	18.0b
	Maize + mulch	10.12a	135.3a	103.8a	31.5a
Leaves	Maize	2.18b	30.4b	25.2b	5.2a
	Maize + mulch	3.94a	35.3a	28.1a	7.2a
Stem	Maize	2.52b	10.6b	8.7b	1.9b
	Maize + mulch	5.00a	18.7a	15.4a	3.3a
Cob cores	Maize	1.94b	9.1b	7.0b	2.1a
	Maize + mulch	2.36a	10.4a	8.1a	2.3a
Aboveground biomass	Maize	12.53b	134.7b	107.5b	27.2b
	Maize + mulch	21.42a	199.7a	155.3a	44.4a
Roots	Maize	1.04b	5.7a	4.4a	1.3a
	Maize + mulch	1.31a	6.5a	5.1a	1.4a

Different letters within a column in each maize segment indicate means differ at $P \leq 0.05$ between treatments.

4. Discussion

4.1. N uptake and fertilizer N recovery by maize

The maize grain yield, biomass production, and N uptake in micro plots were all similar to those in their respective main plots in the 2011 and 2012 cropping years (Liu et al., 2014a; Hai et al., 2015). The significant increases in grain yield, biomass production and N uptake by maize in mulched treatment were attributed to the increase in soil temperature, reduction in soil evaporation and improvement in soil N availability, compared to those in non-mulched treatment (Liu et al., 2014a; Hai et al., 2015).

The measured urea-N recovery by maize in the 2011 season in both treatments with and without mulch was relatively low in comparison to the world cereal grain fertilizer N recovery of 33%, as estimated by Raun and Johnson (1999). This is likely due to the overuse of fertilizer N in the present experiment.

The present study demonstrated that using plastic mulch decreases in-season fertilizer N recovery by maize, contrary to our expectations. The decreased labeled-N uptake by maize in mulched soils in the 2011 cropping season can be attributed to a “dilution effect” of increased soil N availability due to the stimulated N mineralization compared with that in non-mulched soils. We reported that in the 2011 growing season, total N mineralized in the top 15-cm depth of the main plots averaged 112 kg ha^{-1} in mulched soils, contrasting to 54 kg N ha^{-1} immobilized in non-mulched soils; in the 2012 growing season, total N mineralization in the same depth was 347 kg ha^{-1} in mulched soils whereas it was 116 kg ha^{-1} in non-mulched soils (Hai et al., 2015). Due to the increase in mineral N from soil organic matter in mulched soils, the portion of labeled-N in the total soil available N could have been reduced compared with that in non-mulched soils, which in turn decreased the opportunity for labeled-N to be captured by the roots.

In the second season (2012), the increased labeled-N uptake by maize in the plots with mulch was also probably related to the faster mineralization of soil organic N compared to those without mulch (Hai et al., 2015). The organic N transformed from labeled-urea by soil microorganisms in 2011 would belong to a more readily mineralizable pool (Fox, 2004; Gurlevik et al., 2004), which therefore should have been mineralized preferentially over the native soil organic N. Thus, it is very likely that, with increasing soil temperature and moisture due to the presence of mulch (Hai et al., 2015), mineralization of this readily mineralizable organic labeled-N pool increased the enrichment of the mineral labeled-N in the total available N pool during the key time of N mineralization and maize growth in the second season. This in turn presumably resulted in the increased uptake of residual labeled-N by maize in the plots with mulch compared to those without mulch. N fertilization in previous years affects net mineralization of organic compounds in subsequent growing seasons (Motavalli et al., 1992; Azam et al., 1994; Antil et al., 2001). Close monitoring of the allocation of urea-N between organic and inorganic forms in soil during the growth of maize would help to clarify the above hypotheses.

4.2. Unaccounted for urea N

Processes of ammonia volatilization, denitrification and leaching are likely associated with the unaccounted for labeled-N in the urea-fertilized field. At the end of the 2011 harvest, the leaching of both mineral and organic labeled-N was limited within the depth of 170 cm in all treatments; this indicates that N leaching did not significantly contribute the unaccounted for labeled-N in the first season. According to previous evidences (Arriaga et al., 2011; Nishimura et al., 2012; Berger et al., 2013; Liu et al., 2014b), denitrification may not substantially contribute to the differences in N losses between non-plastic-mulched and mulched croplands. Thus, the finding that the unaccounted for labeled-N in the treatments with mulch was 69% less than that in the treatments without mulch, in the 2011 cropping season, suggests that plastic mulch is a physical barrier that reduces ammonia volatilization.

In the 2012 season, in the absence of maize, the higher unaccounted for labeled-N under plastic mulch compared with no mulch indicates that plastic mulch increased N leaching in non-cropped soils. This might been caused by an increase in the downward water-flow due to the reduced evaporation (Liu et al., 2014a) and more abundant labeled-N in soil due to the less ammonia volatilization in 2011, in mulched relative to non-mulched treatments. In 2012, ammonia volatilization had not likely contributed to the unaccounted for labeled-N, because little ammonium from labeled-urea can remain in soil one year after application. However, in the presence of maize, the unaccounted for labeled-N was similar between mulched and non-mulched treatments. This may be because the effect of mulch increasing the downward water-flow in cropped plots is less prominent than in non-cropped plots due to maize transpiration (Liu et al., 2014a). The less labeled-N loss in the cropped soils may result from a smaller labeled-N loading with maize uptake and less downward water-flow in the profile with maize transpiration compared with the non-cropped soils.

The present study has shown that the downward motion of organic N derived from urea can be an important component of N loss from the upper soil layers. This was evidenced by the fact that organic labeled-N in all treatments leached to the same depth as mineral labeled-N by harvest in 2011 (Fig. 2a–d). Further, the majority of organic labeled-N leached to depths below 50 cm in the mulched, non-cropped treatment at harvest in 2012 (Fig. 2f). It is known that microbial-originated organic N is hydrophilic and thus is contributable to the total N leaching from soil profiles (Qualls and Haines, 1991; Gu et al., 1995; Kušlienė et al., 2014).

4.3. Urea N immobilization in soil

We showed that plastic mulch decreases the immobilization of urea-N in soil. This was evidenced by the facts that, at harvest in 2011, the higher contents of total labeled-N in the soils of the treatments with mulch relative to those without were attributed to differences in the mineral fraction. This may be associated with an increase in microbial activity in the soils of the mulched treatments (Liu et al., 2014c; Hai et al., 2015), due to the increased soil temperature and moisture. The mineralization of microbial-assimilated organic labeled-N was stimulated in mulch treatments, compared with that in non-mulch treatments, resulting in a decrease in the net microbial immobilization of urea-N. Both N mineralization and N immobilization processes occur simultaneously in soil (Nannipieri and Eldor, 2009). At harvest in 2011, the finding that the decreased total labeled-N in cropped soils was mainly due to the decreased organic labeled-N fraction relative to no-cropped soils suggests that maize cropping also decreased the immobilization of urea-N in soil. This could also be related to the stimulation of microbial activity and N mineralization when maize was present (Hai et al., 2015).

The greater ratio of organic to mineral-labeled N in the 0–170 cm soil layer with mulch than without mulch in 2012 did not prove an increased immobilization in the former treatment compared to the latter. Firstly, as a result of further downward water-flowing during 2012 in the treatments with mulch, most of the mineral labeled-N (which was more mobile than the organic labeled-N) had been removed by leaching and/or crop uptake from the 170 cm soil profile by harvest (Fig. 2e–h). Secondly, in the treatments with mulch, the organic labeled-N that was microbial-assimilated in the upper soil layer leached to the lower depths, where its mineralization was unaffected by mulch. Therefore, possibly the translocation of labeled-N from the upper to the lower soil layers and/or crop uptake resulted in the greater ratio of organic to mineral labeled-N in the 0−170 cm soil layer with mulch relative to no mulch by harvest in 2012.

5. Conclusions

When plastic mulch was used, the N that accounted for the increase in N uptake by the maize crop came from the soil and was not derived from the applied urea fertilizer. Plastic mulch decreased in-season urea-N uptake, thus decreasing the in-season fertilizer N recovery compared to not using mulch. The decreased labeled-N loss in the 0−170 cm soil profile in mulched treatments in 2011 suggests a blocked ammonia volatilization; whereas the increased labeled-N loss in mulched plots where maize was not cropped in 2012 may be due to the stronger N leaching potential compared to that in the non-mulched plots. Our results indicate that plastic mulch profoundly changes the fate of urea-N in maize production in cold and dry croplands.

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