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Winter Wheat Straw Decomposition under Different Nitrogen Fertilizers

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Abstract: The climate changes and increased drought frequency still more frequent in recent periods bring challenges to management with wheat straw remaining in the field after harvest and to its decomposition. The field experiment carried out in 2017–2019 in the Czech Republic aimed to evaluate winter wheat straw decomposition under different organic and mineral nitrogen fertilizing (urea, pig slurry and digestate with and without inhibitors of nitrification (IN)). Treatment Straw 1 with fertilizers was incorporated in soil each year the first day of experiment. The Straw 2 was placed on soil surface at the same day as Straw 1 and incorporated together with fertilizers after 3 weeks. The Straw 1 decomposition in N treatments varied between 25.8–40.1% and in controls between 21.5–33.1% in 2017–2019. The Straw 2 decomposition varied between 26.3–51.3% in N treatments and in controls between 22.4–40.6%. Higher straw decomposition in 2019 was related to more rainy weather. The drought observed mainly in 2018 led to the decrease of straw decomposition and to the highest contents of residual mineral nitrogen in soils. The limited efficiency of N fertilisers on straw decomposition under drought showed a necessity of revision of current strategy of N treatments and reduction of N doses adequately according the actual weather conditions.

Keywords: decomposition; winter wheat straw; urea; slurry; digestate

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1. Introduction

The fertility and quality of soil depends on the turnover of organic carbon in soils and therefore on the input of organic matter into soils. The soil organic C decomposition rate is responsible for the turnover of organic C pools [1] and hence soil health. The loss of soil organic carbon (SOC) from agricultural soils is a key indicator of soil degradation associated with reductions in net primary productivity in crop production systems worldwide [2].

The straw residues derived from agricultural crops are critical for the maintenance of soil quality and belong also among the greatest sources of soil organic matter in agrosystems [3]. The global production of the winter wheat straw was 529 million tons in 2013 [4] at the global production 710 million tons of grain [5]. The estimated global production of wheat will be about 765 million tons in 2020 [6]. Nowadays straw production can therefore reach about 569 million tons. The global data of straw incorporation in soils are unknown, but the return of crop residues in soils is still more required for maintenance of organic matter in soil. For instance, China which is one of the greatest global producers of wheat accounting for about one–third of the global production proposed returning crop straw to the field soil to practice conservation agriculture [7,8].

The incorporation of crop residues into the soil and its subsequent decomposition replenishes the soil organic matter content [9]. Post-harvest residues as a part of the plant biomass, being a harvest by-products, remain in the field after harvesting and favourably affect soil fertility. They represent an important source of soil organic matter as well as supporting carbon sequestration and soil organic matter (SOM) formation [10].

The fertilization of soils increases straw decomposition relative to the unfertilized soil [11]. High content of mineral nitrogen (Nmin) accelerates the decomposition of light carbon fractions, while further stabilizing soil carbon compounds that are more difficult for decomposition [12,13]. The effect of Nmin on the decomposition of post-harvest residues and the formation of SOM is variable depending also on the N content in post-harvest residues and soil [14,15]. It also depends on the quantity of accessible nutrients and organic compound content, N leaching and the structure of the microbial community.

Nitrogen fertilizers are applied to adjust large C:N ratio of wheat straw to enable soil microorganisms to decompose postharvest residues easily. The carbon content of straw can increase soil C:N ratio, thereby stimulating soil microbial growth and potentially causing competition among microbial groups with different life history strategies [16,17]. However, soil C:N ratio is basically determined by soil organic carbon and total nitrogen [18]. Higher C:N crop residue ratio than soil microbial biomass can change the availability of mineral nitrogen (Nmin) and decrease the rate of microbial decomposition of crop residues [19].

Among mineral fertilizers used for stimulation of straw decomposition, the urea ($CO(NH_2)_2$) is one of the most globally used mineral nitrogen fertilizers [20] and is transformed by enzymatic and microbial processes in soils [21]. Application of animal and other organic residues on arable soil is a common practice. Pig slurry is the mixture of urine, excrements and water and due to its significant nitrogen consisting of inorganic and organic compounds [22] is a valuable fertilizer for crop production. However, its application can pose also significant risks on the environment due to risk of ammonia volatilization or nitrate leaching [23]. Pig slurry was also found to affect straw mineralization on the soil surface whereas less effect was found after incorporation into the soil [24]. Digestates used on agricultural land originating from biogas plants are the organic residues of anaerobic digestion of plant biomass and manures. Their production increases due to increasing number of biogas stations and more and more popular renewable energy [25,26]. Digestates contain considerable quantity of nutrients (namely nitrogen and potassium) suitable as fertilizers on arable land. However, digestate obtained has higher proportions of mineralized plant-available nutrients than the untreated manure and digestion results also in a significant odor reduction [25,27,28]. Straw application together with the digestate is o good source of organic C, easily mineralizable N from digestate supports the degradation of straw and increase microbial biomass and soil microbial activity, while fertilization with digestate itself brings an effect in increasing crop yield, but does not improve the level of soil organic matter significantly [28].

The decomposition of crop residues is governed by both quantity and quality of the residue, climatic conditions such as temperature and moisture, and soil properties [29]. High moisture and temperatures promote the straw decomposition [9]. Soil water content is an important factor that affects the decomposition of crop residues [30], first because soil water potential must be sufficient to provide water for microbial activity [29]. The influence of climate on decomposition of soil carbon has been well documented, but there remains considerable uncertainty in the potential response of soil carbon dynamics to the rapid global increase in reactive nitrogen (coming largely from agricultural fertilizers and fossil fuel combustion) [12]. The decrease of precipitations followed by drought can therefore alter the decomposition processes of post-harvest residues and promote N losses.

The aim of the research was to verify the effect of nitrogen mineral and organic fertilizers on the decomposition of winter wheat straw in summer-autumn period under natural conditions in the years 2017–2019. The effect of N fertilizers on mineral nitrogen content in soils with and without straw incorporated in soils was also studied.

2. Materials and Methods

2.1. Field Experiment

The field experiment with different kinds of N fertilization to enhance the winter wheat straw decomposition was carried out in the years 2017–2019 in Crop Research Institute, Prague-Ruzyně, Czech Republic (50.0891708 N, 14.2964372 E, altitude = 340 m; annual average precipitation = 472 mm; annual mean air temperature = 8.4 °C; soil type = Illimerized Luvisol). The experiment was conducted in field conditions. The microplots made of metallic frames of area 0.25 m^2 were installed after the winter wheat harvest, each treatment had 4 repetitions in randomized design with four horizontal rows for each repetition enabling that no plot was situated in the same vertical line.

The start of the experiment in individual years was as follows: 16 and 17 August 2017; 14 and 15 August 2018; 6 and 7 August 2019. Winter wheat straw was incorporated into soil together with applied nitrogen fertilizers immediately (Straw 1) or straw (Straw 2) was left on the soil surface and application of N fertilizers and their incorporation together with straw took place after three weeks: 11 September 2017; 6 September 2018 and 30 August 2019. Nitrogen fertilizers with straw (Straw 1 and Straw 2) were incorporated up to 10 cm layer of soil. The winter wheat straw decomposition was evaluated in function of used type of nitrogen fertilizer and the current weather in the years 2017–2019.

The straw dose was 8 t ha^{-1} in the year 2017 and 6 t ha^{-1} in 2018 and 2019. The straw of cultivar Tobak (grower: M. von Borries-Eckendorf GmbH and KG, Leopoldshohe, Germany) taken from actual harvest and crushed to pieces of 1–8 cm was used for the experiment. The N fertilizers were applied in the dose 80 kg N ha^{-1} in the year 2017 and 60 kg N ha^{-1} in the years 2018 and 2019.

The fertilizers used in the experiment were: urea, pig slurry, digestate from biogas stations and pig slurry or digestate amended with nitrification inhibitors (IN) [N-Lock (20% Nitrapyrin) in 2017 and Piadin (1.5% Methylpyrazol and 3% Triazol) in 2018 and 2019]. Average characteristics of digestate and pig slurry in years 2017–2019 are given in Table 1. All experimental treatments are given in Table 2.

Table 1. Average characteristics of digestate and pig slurry applied on the wheat straw in the years 2017–2019.

		Digestate	Pig Slurry
Dry matter	%	6.30	5.60
Ntot	%	0.46	0.56
NH_4-N	%	0.32	0.43
pH		8.07	6.97
P	%	0.06	0.07
K	%	0.43	0.22

Ntot–total nitrogen; NH_4-N–ammonium nitrogen; P–phosphorus; K-potassium.

The trial ended after 10 weeks in 2017 (26 and 27 October 2017) and 2018 (22 and 23 October 2018) and after 12 weeks in 2019 (29 October 2019). The straw bags were removed from the soil. Before weighing, the soil was removed from the bags and straw was cleaned by washing in the water. The residual soil was removed by using a water pump equipped with a nylon cover to avoid straw loss. Straw was subsequently dried at 65 °C, weighed and the loss of straw was calculated. Soil samples from a depth of 0–10 cm and 10–30 cm were collected to determine NH_4-N and NO_3-N contents in a soil. The extraction procedure was as follows: 50 g of soil was shaken in 250 mL 1% K_2SO_4 for 1 h at 200 mph and thereafter filtered on Whatman 40 filters. The clear extracts were measured immediately after filtration by means of flow injection SAN^{PLUS} System analyser (Skalar Analytical B.V.; The Netherlands).

Table 2. Treatments in the straw decomposition experiment. (Straw: 0 = treatments without straw; Straw 1 incorporated the 1st day of experiment; Straw 2 = incorporated after 3 weeks of staying on surface).

Treatment	**Straw**
Control	0
Urea	0
Pig slurry	0
Digestate	0
Control	Straw1
Urea	Straw1
Pig slurry	Straw1
Digestate	Straw1
Pig slurry + IN	Straw1
Digestate + IN	Straw1
Control	Straw 2
Urea	Straw 2
Digestate	Straw 2

IN-inhibitor of nitrification.

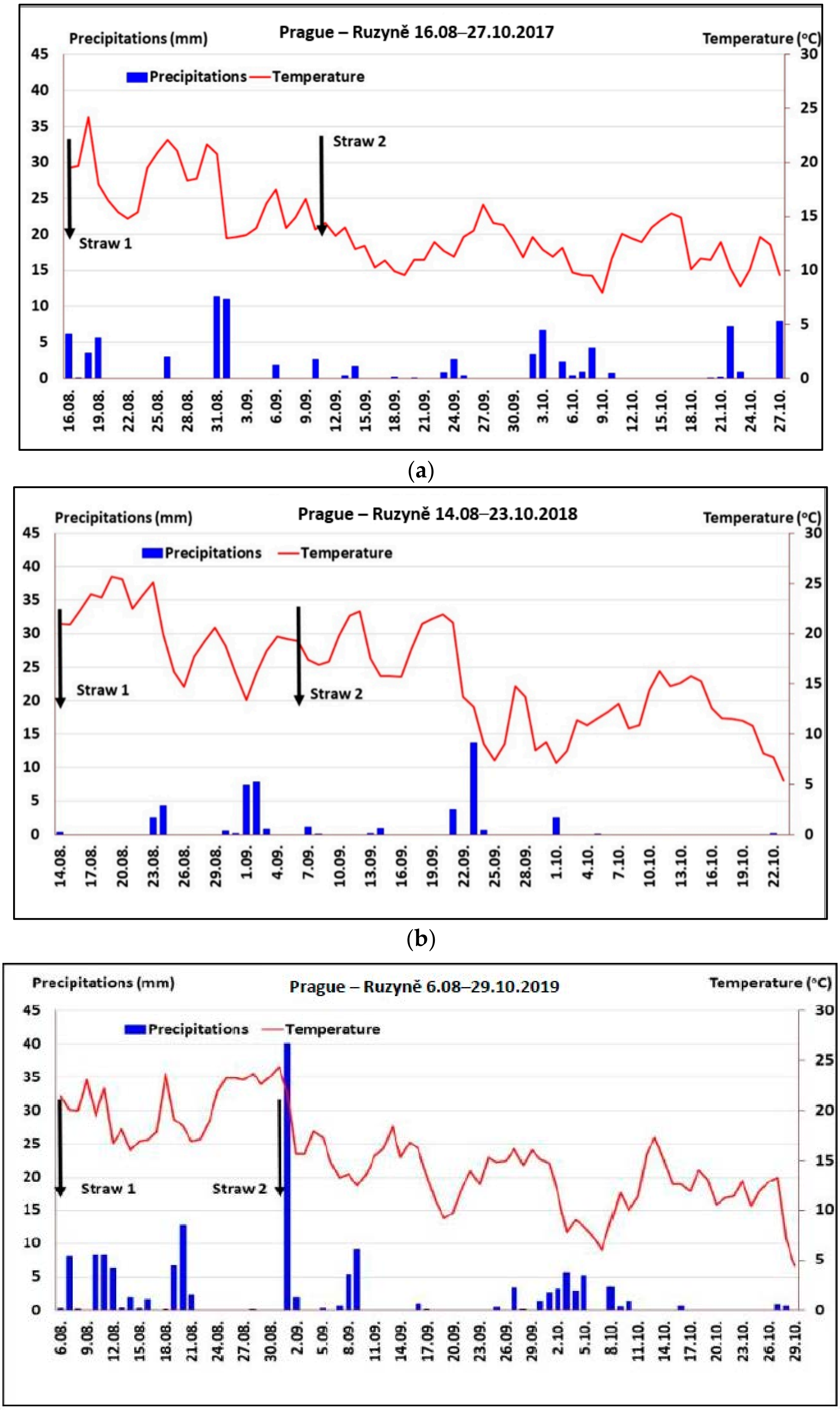
Permeable nylon bags with weighed straw (approx. 1.3 g bag^{-1}) were prepared for the straw decomposition test. Four bags were incorporated in each plot together with major part of straw (approx. 195/145 g plot^{-1}). The corresponding amount of the N fertiliser was applied on the individual bags.

2.2. Precipitation and Temperature

2017: The experimental period 2017 (17 August–27 October 2017) was characterised by the total rainfall of 93.3 mm (August 23.6 mm, September 21.4 mm, October 34.7 mm) while 9.2 mm fell in first 2 days after Straw 1 incorporation and next 3 mm fell on 26 August 2017. Next higher precipitation was on 31 August and 1 September 2017 (together 22.4 mm) after which a substantial decrease of temperatures was noted. The warmer weather (mainly in August) possibly did not allow sufficient straw degradation due to water evaporation and drier soil. Following experimental period was characterised by insufficient precipitations (Figure 1a). The average temperature during the experiment was 14.7 °C.

2018: The experimental period 2018 (14 August–23 October 2018) was characterised by dry and hot weather when the total rainfall during the 10 week field trial was only 47.1 mm (August 7.9 mm; September 36.4 mm; October 2.8 mm), the average temperature was 15.9 °C. The time following straw incorporation was characterised by lack of precipitations and by warm weather (Figure 1b). Despite two short periods of rain (31 August–1 September 2018 and 23 September 2018), these conditions did not allow sufficient straw decomposition.

2019: The experimental period 2019 (6 August–29 October 2019) was characterized by higher rainfall and lower average temperatures during the experiment (Figure 1c) compared to 2017 and 2018. In 2019, total rainfall was 148.3 mm (August 57.5 mm; September 63.8 mm; October 27.0 mm) and the average temperature was 15.3 °C. Unlike in the year 2018, in 2019, the precipitations came soon after the incorporation of straw with N fertilizers. The higher precipitations together with higher temperatures especially in August and early September created more suitable conditions for straw decomposition.



(**a**)

(**b**)

(**c**)

Figure 1. (**a**–**c**): Temperatures and precipitations during field experiments. The arrows indicate dates of straw incorporation.

2.3. Statistical Analysis

Statistical calculations were performed using Statistica 13.0 Software, TIBCO, U.S.A. The results were expressed as mean values from 4 replicates for each treatment and year. Two-way ANOVA was used to evaluate effects of years and treatments on straw decomposition and mineral nitrogen contents. The same letters according the Tukey's test ($p < 0.05$) indicate statistically identical values.

3. Results

3.1. Straw Decomposition and Fertiliser Effect

The straw decomposition differed according ANOVA test among studied years ($p < 0.001$) when the lowest average decomposition was obtained in the year 2018 and the highest in 2019. Significant difference was found also among treatments ($p < 0.001$) and for the combination year and treatment ($p < 0.001$) (Figure 2).

2017: The effect of individual fertilizers and incorporation dates on the decomposition level of straw is shown in Figure 2. Compared to the Straw 1 decomposition in control treatment (21.5 %), N fertilizers increased the straw decomposition to 26.4–32.5%. Comparing the N and organic fertilizers, the lowest Straw 1 decomposition was found after pig slurry (26.4%) followed by application of digestate with nitrification inhibitor (N-Lock) (27.9%). The highest straw decomposition was found under digestate (32.5%), urea (32.0%) and pig slurry + N-Lock (31.9%) treatments. These treatments differed significantly from control according to Tukey test at $p < 0.05$.

The incorporation of Straw 2 after three weeks of laying on the surface showed that the overall straw decomposition in control soils (Straw 1 and Straw 2) was similar. In case of Straw 2 the decomposition on the soil surface (2.8%) was included. The significant increase of Straw 2 decomposition was noted with urea and digestate treatment in comparison with control. However, both urea and digestate affected the Straw 2 decomposition less (in case of urea significantly) than it was observed for relevant treatments of Straw 1.

2018: The straw decomposition in 2018 was lower than in 2017, no straw degradation above 30% was detected in 2018 (Figure 2). During the 10-week experiment, the lowest decomposition of straw was observed in the non-fertilized treatment Straw 1 (23.6%) and Straw 2 (25.3%). The use of different nitrogen fertilizers decomposed the Straw 1 up to 25.8% (digestate)–29.8% (digestate + Piadin). The N treatments differed significantly at $p < 0.05$ from control but together had similar effect on the straw decomposition.

The amendment of nitrification inhibitor Piadin led to slightly different results in comparison with the N-Lock used in 2017. The straw decomposition in 2018 was slightly higher in digestate + Piadin and lower in pig slurry + Piadin treatments in comparison with digestate and pig slurry treatments without inhibitor of nitrification. However, no significant differences among N treatments were found for Straw 1 decomposition.

The decomposition of Straw 2 on soil surface was 5.3% and was influenced by the ongoing weather and especially by drought in 2018. The observed precipitations during Straw 2 laying on the soil surface were only 24 mm and average temperature higher by 2.9 °C (20.2 °C) in comparison with the year 2017 (45 mm; 17.3 °C). Lower straw dose (6 t ha^{-1}) was used in the year 2018 due to its lower yield in this dry year and this fact could be the possible reason for obtaining higher percentage of straw decomposition on soil surface in comparison with the year 2017.

Application of nitrogen fertilizers to the Straw 2 did not affect its decomposition sufficiently. Particularly, the urea treatment reached a decomposition rate similar as control (Figure 2). The application of digestate to Straw 2 led to total straw decomposition of 28.5%.

2019: Total straw decomposition in 2019 was the highest among all tested years (Figure 2). The straw loss averaged around 36% in 2019, compared with 26% in 2018 and 28% in 2017. During the 12-week experiment in 2019, the application of fertilizers (urea, slurry and digestate with and without nitrification inhibitor Piadin) increased straw decomposition to 36.6–40.1% (Straw 1) in comparison with untreated control (33.1%). Tukey test did not show significant differences between these treatments. The decomposition of

Straw 2 during three weeks on the surface reached 14.0%, altogether in control soil it was 40.6%. Application of fertilizers on Straw 2 increased the total decomposition of the straw significantly up to 52.3% (urea) and 50.1% (digestate).

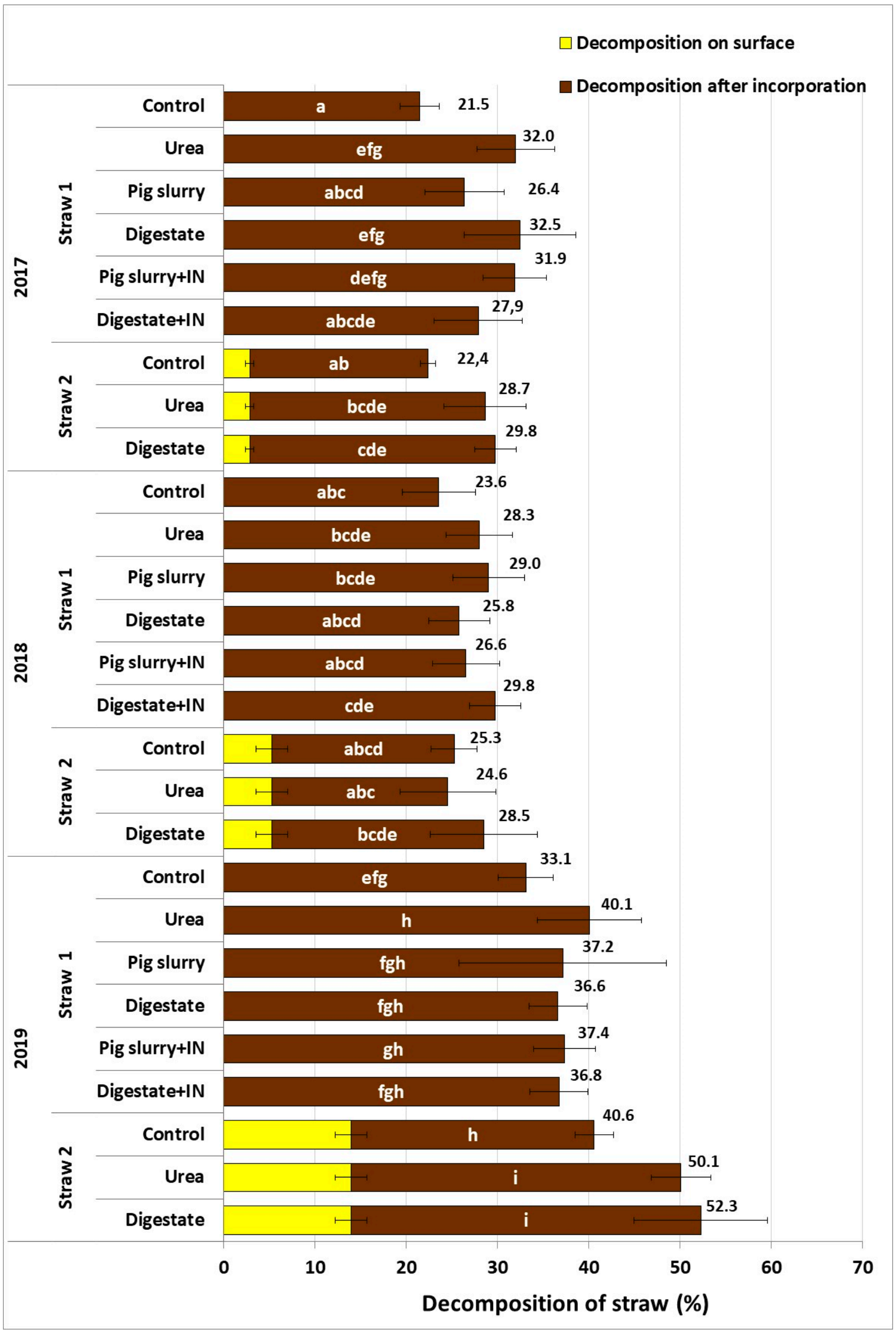


Figure 2. Winter wheat straw decomposition under different nitrogen fertilizers. The same letters "a–i" in figures represent statistically identical values of examined tillage practices according to two-way ANOVA Tukey's test ($p < 0.05$) determining the significant differences among the data. Bars on histograms represent standard deviations. Numbers next to histograms represent cumulative exact values in relevant treatments. IN = inhibitor of nitrification.

3.2. Mineral Nitrogen (Nmin) Content in Soils

The content of mineral nitrogen was composed mainly of nitrates (NO_3-N) which in the layer 0–10 cm differed according ANOVA test among studied years ($p < 0.001$) when the highest average nitrate contents were obtained in the year 2018 and the lowest in 2019. Significant difference was found also among treatments ($p < 0.001$) and for the combination of year and treatment ($p < 0.001$) (Figure 3). No significant difference in nitrate contents was obtained among the studied years in the layer 10–30 cm ($p = 0.223$), whereas significant difference was obtained for treatments ($p < 0.001$) and also for combination of year and treatment ($p < 0.01$). Mostly very low contents of ammonium nitrogen contents were determined in soils. Despite to the significant difference of the combination year × treatment in the layer 0–10 cm ($p < 0.01$) and significant differences found for ammonium N in the layer 10–30 cm (year: $p < 0.01$; treatment: $p < 0.05$; year × treatment: $p < 0.05$), the analysis of Tukey test did not show practically no differences among treatments in all studied years.

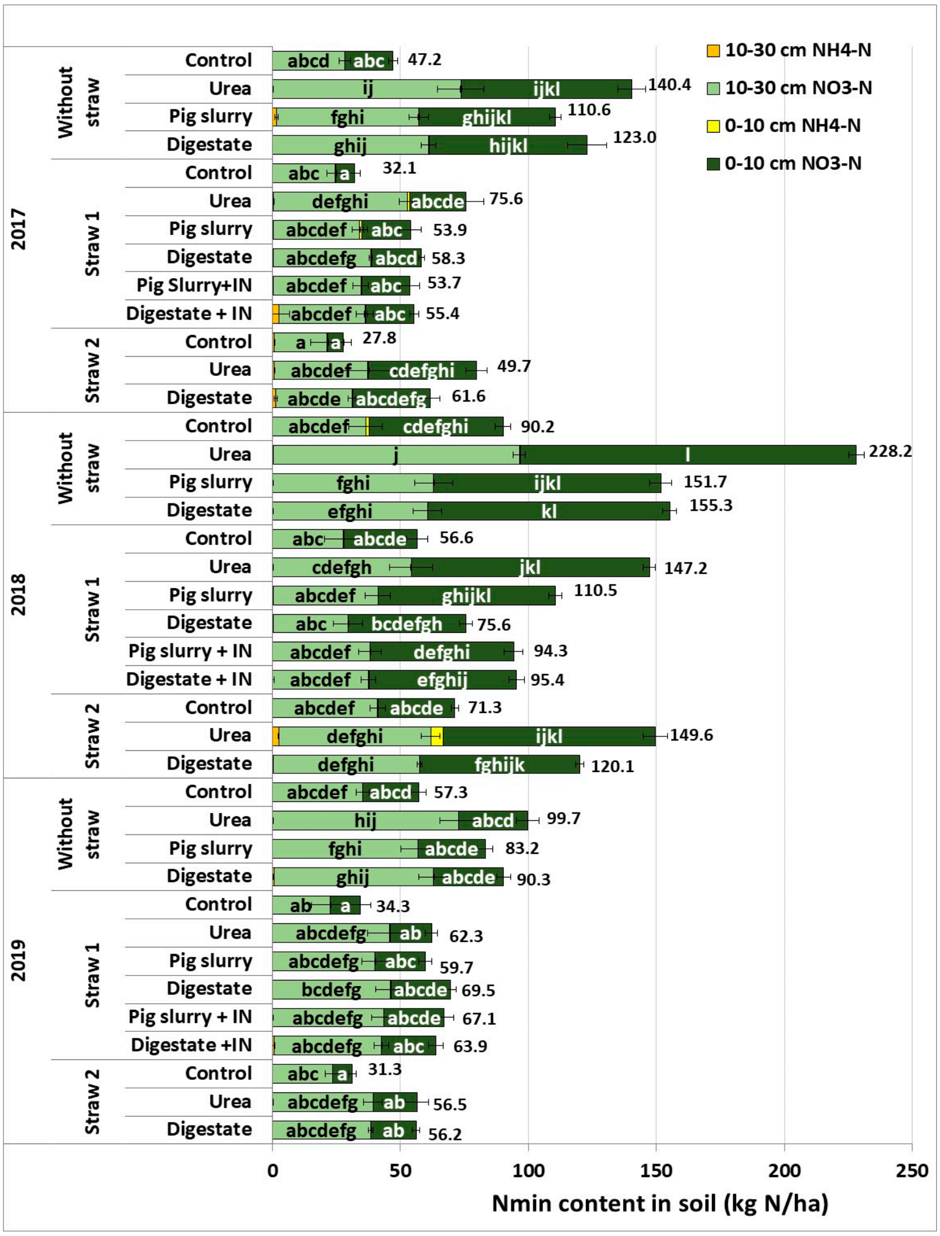


Figure 3. Nmin content in soils under different nitrogen fertilization and straw amendment. The same letters "a–l" in figures represent statistically identical values of examined tillage practices according to two–way ANOVA Tukey's test ($p < 0.05$) determining the significant differences among the data. Bars on histograms represent standard deviations. Numbers next to histograms represent cumulative values of the soil depth 0–30 cm. IN–inhibitor of nitrification.

2017: The Nmin content (mainly NO_3-N) in the control soil non-amended with straw reached 61.6 kg Nmin ha^{-1} in the 0–30 cm profile. The straw incorporation led to the Nmin decrease up to 32.1 kg Nmin ha^{-1} and 27.8 kg Nmin ha^{-1} in Straw 1 and Straw 2 control treatments, respectively (Figure 3). Fertilizer's application increased Nmin contents in soils without incorporated straw significantly. Maximum value (140 kg N ha^{-1}) was found in urea treatment. After application of fertilizers on straw, the Nmin content in soils (pig slurry: 53.9 kg N ha^{-1}; digestate: 58.3 kg N ha^{-1}; urea: 75.6 kg N ha^{-1}) was lower by more than half compared to relevant treatments in soils without straw incorporation. Higher proportion of Nmin was found in deeper soil layer 10–30 cm. The content of Nmin after slurry and digestate application was approximately 15–20 kg N ha^{-1} lower than under urea treatment. Application of a nitrification inhibitor (N-Lock) reduced the Nmin content only slightly. No effect of N-Lock on Nmin content was observed in pig slurry and digestate treatments where only negligible amounts of NH_4-N were determined.

The content of Nmin in soils after incorporation of Straw 2 and fertilizers after three weeks was in the studied soil profile 0–30 cm higher by 5–6% compared to Nmin found in corresponding treatments with Straw 1. The later application of urea and digestate to Straw 2 led to higher proportion of Nmin in the surface layer 0–10 cm in comparison with relevant Straw 1 treatment.

2018: The Nmin content (prevailing NO_3-N) in all soils due to the lack of precipitations was the highest in whole three years of studied period and had also greater portion of Nmin in the surface layer 0–10 cm (Figure 3). The highest content of Nmin was again found in straw-free soil with urea (228 kg N ha^{-1}), lower after application of pig slurry and digestate without straw (152 kg N ha^{-1}, 155 kg N ha^{-1}, respectively). The lowest Nmin content was found in the control soil with Straw 1. Straw 1 incorporation reduced Nmin contents in all relevant treatments: by 37% in control, 35% in urea, 27% in pig slurry and 51% in digestate treatments. In this year, another type of nitrification inhibitor was used, but the effect on Nmin content in soil was not significant.

Straw 2 incorporation with fertilizers after 3 weeks led to very similar Nmin content (150 kg Nmin ha^{-1}) in urea treatment as with Straw 1 (147 kg Nmin ha^{-1}), but with certain proportion of NH_4-N (7.4 kg NH_4-N ha^{-1}). Digestate treatment to Straw 2 increased Nmin content by 59% in comparison with Straw 1.

2019: The Nmin content in soils from the field trial is given in Figure 3. In comparison with 2018, the Nmin content in soil in relevant N treatments was lower by about 40–60%. Similarly as in precedent years, the application of fertilizers to straw-free soil resulted in a higher Nmin content in the soil compared to the soil with incorporated straw. The highest Nmin content in straw-free soils was noted in urea treatment (100 kg Nmin ha^{-1}), followed by digestate (90 kg Nmin ha^{-1}) and pig slurry (83 kg Nmin ha^{-1}). The incorporation of straw together with fertilizers resulted in the decrease of Nmin content in soil to 62–69 kg N ha^{-1} without significant differences among treatments. The application of N fertilizers to Straw 2 led in the year 2019 to lower Nmin contents in a soil in comparison with Straw 1 (about 56 kg N ha^{-1}).

4. Discussion

Based on our results, the straw decomposition was higher in 2019 in comparison with the year 2017 and particularly with the year 2018. The precipitations achieved over the duration of experiments were 93 mm in 2017, 47 mm in 2018 and 148 mm in 2019. In addition, almost no rain was noted in days following the straw incorporation in soil in 2017 and 2018. These conditions did not allow the gradual straw decomposition as the water limitations negatively affect mineralization of fresh plant litter in soils [31].

The digestate or pig slurry treatments showed often similar straw decomposition as urea. This was despite to declared lower nitrogen efficiency of these liquid fertilizers of about 60% in comparison with mineral fertilizers [32]. This may be due to the composition of liquid fertilizers and low dry matter content (typically about 6–7%) which in dry periods could moisten and better adhere to the straw and therefore enhance the soil microbial and enzyme activities. In fact, the increases in straw decomposition are significantly correlated with abundances of total bacteria, fungi and activities of cellulose-degrading enzymes [33].

The higher precipitations in 2019 (147 mm) resulted in higher straw decomposition up to 40% in Straw 1 treatment with urea and 52% in Straw 2 with digestate treatment which are in a good agreement with Turk and Mihelič [34] who in a field experiment found that 44% of wheat straw was decomposed in two months. An adequate precipitation is required for the sufficient straw decomposition regardless whether the straw is incorporated in the soil immediately with N fertilizers or left for some time on the surface. In fact, straw decomposition was found to be faster in areas with higher mean annual temperatures and total precipitations [35–37]. Water and residue quality interactions affecting the decomposition and N dynamics should be therefore considered in residue management strategies for soil protection and nutrient cycling [38].

The effect of nitrification inhibitors on straw decomposition remains unclear. Our experimental results in digestate or pig slurry treatments during all three years of the experiment showed the inconsistent straw decomposition (higher or lower). In addition, in the year 2019, no effect of nitrification inhibitor was observed on straw decomposition possibly due to better weather conditions for the process to occur. The presumption that addition of nitrification inhibitors added to the digestate or slurry should improve straw decomposition due to longer persistence of NH_4-N beneficial for utilization by soil micro-organisms [39], seems to be less functional particularly in more rainy years. In an incubation experiment Vargas et al. [40] showed that addition of N fertilizer with nitrification inhibitor did not affect soil respiration, however they found significantly lower N_2O emissions from soils indicating N immobilization in soils with incorporated straw.

The decomposition of Straw 2 incorporated after three weeks of staying on the soil surface was effective practically only in more rainy year 2019 when it reached maximum of 52.3% in digestate treatment. The Straw 2 decomposition in 2019 on the soil surface reached 14% and the next decomposition after incorporation in the soil during the rest of period (nine weeks) was practically the same as of the Straw 1 during whole 12 weeks experiment. This was possibly due to previous partial straw decomposition on the soil surface (under repeated precipitation).

In all studied years, slightly higher total decomposition of Straw 2 was observed after the application of digestate in comparison with urea. This may be due to better contact of liquid digestate with straw (important particularly in dry years 2017 and 2018) which could promote also soil microbial activities. In fact, Sandor et al. [41] reported that short-term variation of weather had a significant effect on microbial biomass with dry periods distinguished by a reduced microbial biomass compared to wet periods.

Weather conditions in the years 2017–2019 affected also Nmin contents in soils. The year 2018 was exceptional due to very low precipitations. In consequence, higher Nmin content was found in the studied soil profile 0–30 cm and particularly higher proportion of Nmin remained in the soil surface layer 0–10 cm in comparison with the other studied years 2017 and 2019 (Figure 3). In addition, the low straw decomposition probably did not allow the sufficient nitrogen immobilization. In the wetter summer of 2019, the fertilizers application did not show so high Nmin contents in the experimental soils compared to 2018, which could be caused by partial N shift into deeper layers of soil after the intensive precipitation in early September 2019 as suggested by higher NO_3-N contents found in deeper soil layer in our experiment (Figure 3).

As already reported, the straw incorporation led to reduced N loss [42], nitrogen immobilization in the soil and to newly synthetized soil microbial biomass [39,43,44] and these reports are in accordance with our observations. We found lower Nmin contents in soils with applied straw in comparison with soils without straw, and also in years with more intensive straw decomposition.

Due to repeated precipitations in 2019, the conditions for the straw decomposition in soil were more favourable than in 2018 and 2017. Yet even in a more favourable year 2019, the maximum straw decomposition in N treatments reached maximum 40.1% in comparison with control untreated soil (33.1%). The question is whether it makes environmental and economical sense, especially in dry years, to use the nitrogen fertilizers to enhance straw degradation, when more unused nitrogen may remain in the soil after harvesting. In fact, additional amounts of nitrogen can be released from the soil in the process of mineralisation of organic matter, which is moreover intensified by nitrogen fertilization.

We could assume that applied nitrogen can support the activities of soil microorganisms, which use carbon from labile soil organic matter and not from straw, which begins to decompose later. In fact, the fertilization of soil with compost and mineral N affects slightly soil total organic C but increases total N and soil microbial biomass [45].

In addition, new wheat cultivars resistant to fungal diseases [46] and variety of pathogens [47] were bred to improve crop health and yields. However, more resistant cultivars may negatively affect their straw decomposition in soils. The cultivar Tobak used in this experiment resists multiple diseases attacking winter wheat, mainly mildew, *Septoria* leaf blotch, yellow and brown rust. Lower resistance is reported to *Fusaria* [48]. These characteristics support the assumption that observed lower straw decomposition can be related also to the higher resistance to diseases.

The global amount of wheat straw incorporated into the soil is not clear, but it is an option for farmers without livestock production to increase the organic matter content of the soil. Straw incorporation is also one of the most widespread agrotechnical practices [49]. However, many farmers have economic interests and often sell straw for bioenergy purposes or burn it in the field. On the contrary, many other farmers appreciate the use of straw incorporation for its beneficial effects on soil organic matter content, improving soil structure, nutrient supply, etc. According to a rough estimate made in Western Europe [50], around 20% of straw production can be incorporated into the soil. Globally it can exceed 100 million tons. Therefore, up to tens of millions tons of nitrogen fertilisers per year can be therefore applied to straw. Our results show that the lower nitrogen treatment of straw incorporated in soils applied with respect to the current temperature and precipitations conditions can save a substantial amount of fertilizers. In changing weather conditions and especially under drought, this strategy can pose a significant environmental problem as well as significant economic losses due to the unnecessary application of nitrogen fertilisers to straw.

5. Conclusions

The results of the three years of our field experiment show an effect of the irregularity of precipitation and the variation of straw decomposition depending on current weather conditions. The limited efficiency of fertilisers on straw decomposition was noted not only under drought in 2018, but also in more favourable weather conditions. According to our observations, the straw decomposition was relatively only slightly increased under N treatments in comparison with non-treated control soils. In view of our results, we recommend mainly in more rainy weather to keep the straw on the soil surface for several weeks with subsequent incorporation into the soil together with N fertilizer, amount of which should be adjusted to current weather conditions and also with regard to nutrient needs of the following crop. In addition, we observed higher decomposition of straw kept several weeks on the soil surface with use of liquid fertilizers (digestate) better adhering to straw. In summary, the weather pattern, the type of fertilizer, and the timing of the straw incorporation into the soil need to be considered and managed in concert to achieve the most environmental and economical management of agricultural land.

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