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Shredding corn stubble during harvest: Insights from four years of on-farm experiments

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Corn stubble remaining in the field after grain corn harvest plays a central role in integrated pest and residue management. This study investigated the integration of corn stubble shredding into the harvesting process using the "Horizon Star* III" (HS3) header equipped with flail knives. Over four years and seven experimental sites, the single-step method was compared with conventional post-harvest flail mowing. Under favorable conditions, both methods achieved similarly high shredding intensities for non-overrun corn stubble (>84% fully destroyed). A key advantage of the HS3 was its superior performance in overrun areas, where conventional flail mowers showed a marked decline in effectiveness. The parameter node-to-lowest-working-plane distance, which combines soil surface condition and node-to-ground distance, was identified as a key factor influencing corn stubble shredding intensity. The results demonstrate the potential of the HS3 to enhance field-wide shredding performance and point to promising opportunities for methodological advancement in future research.

Keywords
Corn header, flail mower, corn stubble, corn stalks, european corn borer, node-to-ground distance

Corn (*Zea mays L.*) is one of the most significant cash crops globally, playing a crucial role in food security, animal feed, and biofuel production (OECD/FAO 2024). After harvest, substantial amounts of crop residues, consisting of corn stover and corn stubble, remain in the field. Corn stubble refers to the portion of stalks that remain rooted in the soil after harvest, while corn stover includes all plant parts lying loosely on the soil surface, such as stalks, leaves, cobs, and husks (Pordesimo et al. 2004, Shinners and Binversie 2007, D'Amours et al. 2008, Lizotte et al. 2009). While corn stover can be utilized for bioethanol production, biomass power plants, or livestock use, its secondary use remains limited in Europe, with most residues left to decompose on-site (Fleschhut et al. 2016, Miranda et al. 2021, Aghaei et al. 2022). Regardless of potential secondary uses for corn stover, corn stubble always remains in the field.

The management of corn residues is a key aspect of the corn production chain, serving multiple objectives. These include agronomic objectives focus on creating suitable conditions for the following crop (Sindelar et al. 2013, Hou et al. 2022) and nutrient management objectives aim to accelerate residue decomposition and enhance nutrient release (Stetson et al. 2018, Vogel and Below 2019). Phytosanitary goals seek to control pests like the European corn borer (ECB; *Ostrinia nubilalis*) and reduce infection pressure from pathogens like *Fusarium* spp. (Kirchmeier and Demmel 2008, Latsch et al. 2010, Grosa et al. 2016, Schneider and Lenz 2017, Zastempowski et al. 2024).

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Corn stubble management for ECB control

Corn stubble plays a crucial role in the context of ECB management. The primary damage caused by ECB results from larval feeding inside the corn stalks and ears, disrupting water, nutrients, and assimilate transport. This internal tunneling weakens the mechanical stability of the plant, making it more susceptible to stalk breakage, which can lead to harvesting difficulties and increased ear losses (Melchinger et al. 1998, Saß et al. 2007, Mason et al. 2018). In cases of heavy infestation, yield losses in grain corn can range from 5% to 40% (Götzke and Schröder 2007, Lenz 2007, Meissle et al. 2010). Beyond direct crop damage, ECB-induced wounds in the plant tissue serve as entry points for fungal pathogens, particularly Fusarium spp., further compromising yield quality (Sobek and Munkvold 1999, Gatch and Munkvold 2002, Saß et al. 2007, Blandino et al. 2015, Scarpino et al. 2015). By the time of corn harvest, the majority of ECB larvae are located inside tunnels within the corn stubble, typically within the lower 30 cm of the stalk or from the second node downward, where they use the protected space for overwintering (Schaafsma et al. 1996, Schneider and Lenz 2017, Zastempowski et al. 2024). Therefore, shredding corn stubble is a recommended measure for preventive ECB control, as it destroys the insect's winter habitat and helps to reduce the population surviving into the subsequent growing season (Uppenkamp 2012, Freier et al. 2015).

Previous studies have demonstrated the effectiveness of corn stubble shredding in controlling the ECB by comparing larval counts before and after shredding (Seidel et al. 2014, Freier et al. 2015, Grosa et al. 2016, Schneider and Lenz 2017). However, the precise relationship between the degree of stubble destruction and ECB larval mortality remains largely unexplored. It is assumed that merely crushing the stalks, such as by driving over them, is insufficient to eliminate the ECB's overwintering habitat (Klingenhagen et al. 2014). For effective control, corn stalks and stubble must be shredded to a degree where they no longer provide sufficient space for the approximately 25 mm long larvae to overwinter or allowing water to penetrate (Schorling 2005, University of Minnesota 2025). Therefore, the common objective is to completely destroy the corn stubble and shred it down to the root base.

Technical approaches for shredding corn stubble

The shredding of corn residues begins during harvest, with the configuration of the corn header playing a crucial role in determining the intensity of residue shredding. The intensity is primarily influenced by the design of the snapping rolls and the use of additional attachments such as horizontal choppers. Most corn headers focus on shredding the stover while leaving the stubble intact and anchored in the soil. The only adjustable factor in this process is the stubble height, which can be adapted by altering the cutting height (Handler et al. 2005, Dutzi 2019, Ramm et al. 2024).

Typically, an additional post-harvest operation is required to shred corn stubble. For this purpose, various specialized implements have been developed. One example is the "Zünslerschreck® aktiv" by Knoche Maschinenbau GmbH (Bad Nenndorf, Germany), which uses "Stoppelmaxx" friction wheel modules by Baß Antriebstechnik GmbH (Gebsattel, Germany) to shred stubble by twisting it. Another is the "Stoppelschlitzer" by terratec GmbH (Halle/Westfalen, Germany), which presses the stubble into the soil and slices it laterally using blades (Uppenkamp 2016). More recently, Zastempowski et al. (2024) introduced a newly developed mechanism that not only shreds the above-ground stubble but also targets the root system. This is achieved by undercutting the soil and extracting the stubble along with its root system, which is then shredded using two vertical shafts equipped with discs to which flails are mounted. Additionally, multi-purpose implements such as disc harrows and knife rollers, as well as rotary and flail mowers used for more intensive processing, are commonly employed. Field studies and trials have investigated a variety of implements for corn stubble shredding across forage, grain, and corn-cob-mix production systems. Most of these studies are published as gray literature, including project reports and articles in professional magazines, with considerable variation in the methodologies used to evaluate shredding intensity, making direct comparisons between results challenging. Assessments typically include measurements of stubble height and ratings of the structural integrity of corn stubble, though the criteria for distinguishing between different levels of destruction often differ between studies. In some cases, sieve analyses were also conducted to characterize the shredded corn residue. Nevertheless, several studies consistently indicate that flail mowers achieve the highest corn stubble shredding intensity, as evidenced by short residual stubble height and relatively low numbers of stubble with intact internodes, making them a preferred choice for this application (Latsch et al. 2010, Uppenkamp et al. 2011, Seidel et al. 2014, Grosa et al. 2016, Uppenkamp 2016, Schneider and Lenz 2017, Uppenkamp and Furth 2020). Despite their overall effectiveness, flail mowers face significant challenges when processing overrun, flattened, or bent corn stubble. When stubble lies on the ground or lacks sufficient structural resistance, it may not be effectively engaged by the tools of flail mowers, resulting in longer residual stubble and an overall reduction in processing quality (Uppenkamp et al. 2011, Klingenhagen et al. 2014, Grosa et al. 2016, Brunotte and Vosshenrich 2017, Schneider and Lenz 2017). Additionally, Grosa et al. (2016) noted that the direction of flail mowing had an additional notable effect: mowing in the same direction as the orientation of the flattened stubble resulted in longer residual stubble compared to mowing against the orientation.

Depending on the working width of the corn header and the design (front or rear attachment) and working width of the flail mower, significant portions of the field may have been traversed by the vehicles' tires or tracks before being processed by the flail mower. In the case study by Augustin et al. (2020), the proportion of area covered by the tires of the forage harvester (front tires: 800/70R38; rear tires: 600/65R38), operating at a working width of 6 m, during silage corn harvest was estimated at 36.1% of the total field area (based on modeled tracks derived from GPS position data). The working width of the forage harvester was identical to that of the corn header investigated in this study. Furthermore, the driving patterns of forage harvesters and combine harvesters are comparable if grain corn is unloaded on the go. The tracks created by vehicles used for the transportation of the harvested crop must additionally be considered. If a flail mower is used as a rear-mounted implement, the tractor tracks also need to be taken into account. Therefore, it can be assumed that with a working width of 6 m for the corn header, more than 35% of the total field area is regularly traversed during grain corn harvest.

In addition to the reduced shredding performance in areas where corn stubble has been overrun, the fact that conventional corn stubble shredding requires an additional post-harvest field pass has led to growing interest in developing solutions that combine harvesting and stubble shredding into a single operation. This concept is not new, Kirchmeier and Demmel (2008) studied the effects of corn residue shredding and tillage techniques on *Fusarium* infections in winter wheat. In their study, flail mowers were mounted on the corn header and the combine harvester to process the corn stubble and corn stover during the harvesting process. However, commercially available corn headers with integrated stubble shredding functionality have only emerged in recent years. Previously, only custom solutions or aftermarket modifications were available, such as the actively driven friction wheel modules “Stoppelmaxx” by Baß Antriebstechnik GmbH (Gebsattel, Germany), which could be retrofitted onto corn headers to shred corn stubble. Additionally, passive stalk rollers are available as retrofit solutions, like the “5000 Stalk Devastator™“ by Yetter Manufacturing Co., Inc. (Colchester, IL, USA). The “StalkBuster” by Maschinenfabrik Kemper GmbH & Co. KG (Stadtlohn, Germany), introduced in 2017, was the first commercially available corn header with integrated stubble shredding functionality specifically designed for forage harvesters used in silage corn harvesting. This header is equipped with a swing-mounted unit for each corn row, where rotating flails shred the corn stubble during the harvesting process. The “Horizon Star* III” (HS3) corn header, introduced in 2019 by Carl Geringhoff GmbH & Co. KG (Ahlen, Germany) and developed within this joint research project, was the first corn header for combine harvesters that integrated stubble shredding into the harvesting process of grain corn. It incorporates a novel toolset for horizontal choppers (flail knives) and the ability to guide the cutting tools close to the soil surface to efficiently shred corn stubble near ground level. For a comprehensive examination of the technical details and factors influencing its power consumption, refer to Ramm et al. (2023). In 2022, CLAAS Selbstfahrende Erntemaschinen GmbH (Harsewinkel, Germany) introduced the “Corio Stubble Cracker” corn header. The “Corio Stubble Cracker” system combines two rotating skids into one unit. Each skid follows one row of corn stubble, with the additional units mounted on swinging arms at the rear of the corn header to follow the ground contour. Each skid is equipped with two hammers to shred the corn stubble (Herter and Schwaer 2022). Thus, at present, two models of grain corn headers are available for processing corn stubble during harvest.

Research objectives

Given the wide range of available equipment for corn stubble shredding and the diverse approaches used to evaluate processing performance, a key practical question arises: Which technical approach or mechanism achieves which level of shredding intensity under specific field conditions? This, in turn, raises further questions regarding how shredding intensity can be reliably measured, which influencing factors should be considered to accurately describe site-specific conditions, and which assessment methods are best suited for this purpose.

Due to the technical characteristics of the machinery, such as large working widths and the need for consistent driving speeds, such investigations are best carried out in large-scale field trials, with on-farm experiments offering particularly suitable conditions. In this context, the rating system published by Brunotte and Vosshenrich (2017) serves as an appropriate starting point for the further development of evaluation methods. The system was originally designed to help farmers to assess field conditions after corn harvest in order to determine the suitability for flail mower use. It also provides a basic framework for evaluating flail mower performance based on the degree of corn stubble shredding.

In this project, the intensity of stubble shredding achieved by the HS3 corn header was validated. Over a period of four years, on-farm experiments were conducted across seven trial sites. During these trials, the stubble shredding performance of the HS3 was compared with various models of flail mowers, with a variant where the stubble remained unshredded serving as the control. The aim of this paper is twofold: (1) to present the methods that have been continuously refined over the course of this project for capturing factors influencing the intensity of stubble shredding, and (2) to provide a comparative assessment of the HS3 corn header with flail mowers used post-harvest, considering the factors that describe the operating conditions.

Material and Methods

Experimental approach

The on-farm experiments included three treatments (Table 1). As a single-step method treatment for corn stubble shredding, the "Horizon Star* III" (HS3; Carl Geringhoff GmbH & Co. KG, Ahlen, Germany) corn header was used, which shreds the corn stubble during the harvesting pass. Since tractor-driven flail mowers are regarded as the most effective option for post-harvest corn stubble shredding, as outlined in the Introduction, they were included as a benchmark in the two-step method. To distinguish the effects of stubble treatment, conventional harvest without stubble shredding was implemented as a third treatment and served as the control.

Table 1: Overview of corn stubble shredding methods evaluated in this research

Treatment	First Pass: Harvest (Configuration of the HS3)		Second Pass: Post-Harvest Residue Management
	Cutting Tools	Cutting Height Setting	
Single-step method	Flail knives	Lowest possible	None
Two-step method	Standard knives	15–25 cm stubble height	Tractor-driven Flail Mowers
Control	Standard knives	15–25 cm stubble height	None

The HS3 corn header is designed to harvest eight rows with a row spacing of 75 cm. Each row unit is equipped with a horizontal chopper, fitted with two cutting tools. These specialized cutting tools consist of a sharp cutting edge and a dulled flail at the end of the tool. When operated close to the soil surface, the flail knives can break down the corn stubble all the way to the root base. The sharp cutting edge performs the horizontal cut, while the dulled flail hits and shreds the corn stubble (Figure 1).

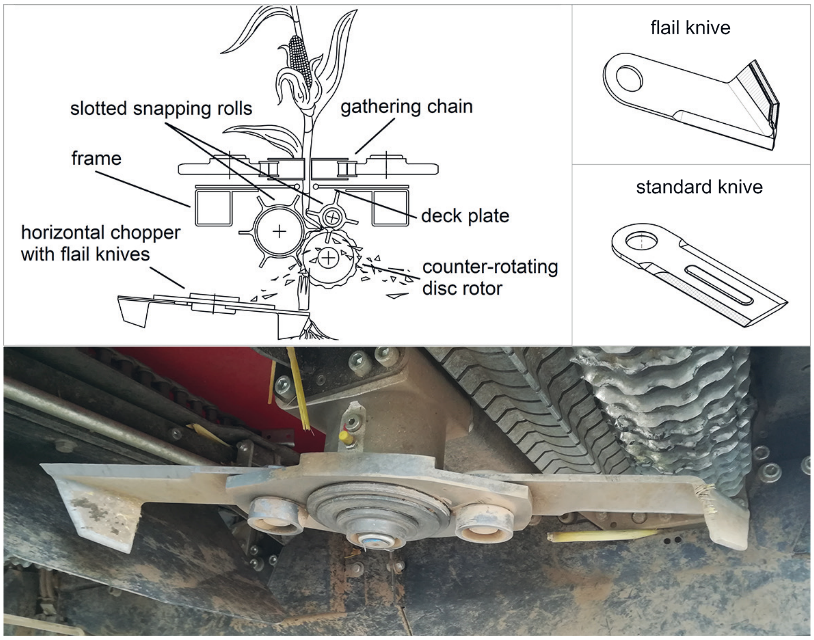


Figure 1: Structural diagram of the „Horizon Star* III" row unit and the tested cutting tools for the horizontal choppers (top row, adapted with permission from Carl Geringhoff GmbH & Co. KG, 2023) and a photograph of the row unit with the horizontal chopper equipped with flail knives (bottom, © S. Ramm)

The technical details of the HS3 have already been described by Ramm et al. (2023). The HS3 was utilized in two different configurations concerning the cutting tools. When equipped with the newly developed flail knives, the corn header was operated at the lowest possible cutting height setting to achieve the desired stubble shredding effect (Table 1). When the flail knives were replaced by standard knives (simple straight knives), the functionality corresponded to that of the conventional "Horizon Star* II" (HS2) corn header, without the ability to shred corn stubble. In this configuration, the cutting height was set to 15–25 cm, a typical stubble height in practice that can be easily achieved with conventional corn headers, which, in contrast to the HS3, are not specifically optimized for operation extremely close to the soil surface (Table 1). At the same time, this setting ensured that the corn stubble could be processed unhindered by flail mowers, i.e., without colliding with the mower housing and being bent over. During the harvest, a constant speed of 6 km/h was maintained.

On-farm experiments were conducted at seven different sites across Germany from 2018 to 2021. These sites spanned from Baden-Württemberg in the south, through North Rhine-Westphalia and Lower Saxony, up to Schleswig-Holstein in the north, thereby representing the conditions of Germany's grain cultivation regions. The field trials were designed as randomized complete block designs. The plot width corresponded to the working width of the corn header (6 m). Due to site-specific conditions such as field size, tramline spacing, topography and the ongoing refinement of the methods applied, adjustments to the number of replications and plot lengths were necessary for the test sites (Table 2).

Table 2: Test sites

Year	Site	Flail Mower	Plot Length in m	Blocks
2018	Zeutern (49.1786, 8.6587)	Sauerburger (Y-Blades)	125	3
2018	Steinheim (51.8460, 9.1316)	Müthing (Hammer flails)	125	3
2019	Stettfeld (49.1858, 8.6343)	Maschio (Hammer flails)	75	6
2019	Bückeburg (52.2676, 9.0851)	Müthing (Hammer flails)	75	6
2020	Kraichtal (49.1442, 8.7332)	Sauerburger (Y-Blades)	75	6
2020	Timmaspe (54.1348, 9.8916)	Sauerburger (Hammer flails)	75	5
2021	Wöbs (54.0690, 10.4754)	None	75	6

All tractor-driven flail mowers and combine harvesters were provided by the respective experimental farms. All combine harvesters were equipped with track systems. At the Steinheim, Bückeburg, Stettfeld, and Kraichtal sites, "Claas Lexion 760 TT" models were used. At the Timmaspe site, an "MF AGCO Ideal 8T" was employed, and at the Wöbs site, an "MF AGCO Ideal 9T". Due to the track width and gauge of these machines, the combine harvesters continuously drove over two rows of corn stubble during harvesting. Given that the corn header had a working width of eight rows, which also matched the width of the experimental plots, 25% of the corn stubble was driven over. The Zeutern site represents an exception. There, a "Claas Lexion 770 TT" (track gauge: 2.86 m; track width:

635 mm) was used. Owing to its specific undercarriage configuration, only a few corn stubbles were sporadically affected by the tracks. As a result, overrun corn stubble was not investigated at this site.

Due to a malfunction of the header height control system at the Stettfeld site, the corn header could not be operated as close to the ground as intended. As a result, no data from the single-step method treatment is available from this experimental site. At the Wöbs site, snowfall following the harvest prevented the use of the flail mower, and consequently, no results from the assessment of corn stubble shredding intensity of the two-step method treatment are available from this site.

The plot boundaries were marked with spray paint and surveyed before harvesting using the "SST FieldRover II 10.4" software (SST Development Group Inc., Stillwater, OK, USA). This software visualizes and stores GPS positioning data, which is transmitted by the RTK-GPS rover (AgGPS 442; Trimble Inc., Sunnyvale, CA, USA) to the laptop.

Assessment of corn stubble structural integrity and influencing factors

In 2017, Brunotte and Vosshenrich (2017) published a rating system designed to help farmers assess field conditions after corn harvest to determine the suitability for flail mower use. The system also provides a framework for evaluating flail mower performance based on the degree of corn stubble shredding. The methods applied during the first year of this study closely followed this system, with minor adjustments to suit the experimental context, and were further refined as the study progressed. Following the stubble treatment, the level of corn stubble shredding intensity was evaluated. The rating system used for this evaluation, shown in Table 3, is based on the five-level system developed by Brunotte and Vosshenrich (2017). For this study, more precise definitions of each rating level were established, specifying the key characteristics required to classify stubble into the respective categories.

Table 3: Scoring system for evaluating the level of corn stubble shredding intensity

Scoring level	Definition
1	Corn stubble is completely frayed, or the sidewall is at least 50% opened
2	Between 30% and 50% of the corn stubble's sidewall is opened
3	Less than 30% of the corn stubble's sidewall is opened, yet clearly damaged
4	Frontal section of the corn stubble is opened, node is missing, sidewall is mostly undamaged
5	Corn stubble is intact, both the frontal section and sidewall are undamaged

(adapted from Brunotte and Vosshenrich 2017)

This evaluation focused on all corn stubble still rooted in the soil. When multiple internodes were present, classification was based on the least damaged internode or the internode corresponding to the highest rating level. Internodes shorter than 3 cm were excluded from the evaluation because a minimum length of 3 cm was considered necessary for European corn borer larvae (*Ostrinia nubilalis*) to overwinter (Schorling 2005, University of Minnesota 2025). Consequently, short internodes located close to the ground were not considered. The evaluation was conducted separately in areas traversed by the combine harvester's tracks and tires and unaffected areas, with stubble randomly selected within each zone.

The results of the corn stubble shredding intensity assessment presented in the Results section are aggregated, showing the mean relative frequencies for completely destroyed (Level 1), damaged

(Levels 2–4), and intact (Level 5) corn stubble, differentiated by non-overrun and overrun corn stubble, as well as by site and treatment. Detailed representations of the results, broken down by all five rating levels and blocks, can be found in Table A1 to Table A7 in the Appendix).

In addition to assessing the intensity of corn stubble shredding, stubble height was also measured. The procedure for measuring stubble height was adjusted starting from the second experimental year. As shown in Figure 2, separate measurements were taken for the height of the solid stubble segment and the total height of the corn stubble.

Figure 2: Corn stubble height measurement scheme (© S. Ramm)

The results of the corn stubble total height and solid stubble segment height measurements presented in in the Results section are aggregated, showing the mean and standard deviation, differentiated by non-overrun and overrun corn stalks, as well as by site and treatment. Detailed representations of the results by block can be found in Table A8 to Table A14 in the Appendix.

Consistent with the rating system published by Brunotte and Vosshenrich (2017), an additional assessment of soil surface conditions was conducted during the first experimental year in the two-step method treatment plots. Soil surfaces were categorized into three distinct types: corn stubble standing on a ridge, on a level surface, or in a depression (Figure 3).

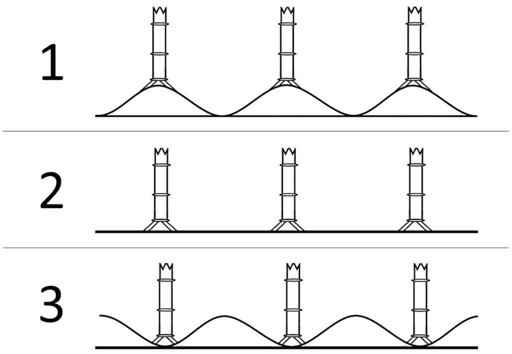


Figure 3: Scoring system for evaluating the soil surface condition (adapted from Brunotte and Vosshenrich 2017)

During the first experimental year, the importance of soil surface condition for successful corn stubble shredding became evident, particularly in relation to the position of the lowest node of the corn plant. Based on these insights, the method for assessing soil surface conditions was refined, and an additional pre-harvest assessment step was introduced.

Starting from the second experimental year, the initial rating scale for assessing soil surface condition (Figure 3) was replaced. To assess soil surface conditions, a 130 cm aluminum profile was placed across the corn rows on the soil surface as a reference. From this reference point, the depth of depressions or the height of ridges on which the corn stubble stood was measured (Figure 4). Measurement of soil surface conditions was subsequently conducted for all treatments and integrated with the evaluation of corn stubble shredding intensity rather than performed as a separate assessment step.

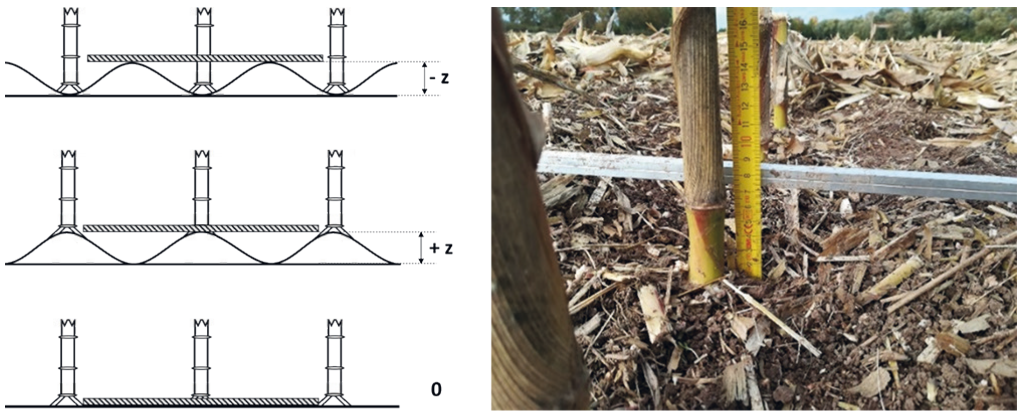


Figure 4: Measurement scheme for assessing soil surface conditions (© S. Ramm)

Additionally, the distance between the lowest node and the soil surface (node-to-ground distance) was introduced as a pre-harvest assessment in the standing corn crop (Figure 5). Consistent with the procedure used for assessing stubble shredding intensity, internodes shorter than 3 cm were excluded from measurement, and the next higher node was used as the reference point.

Figure 5: Scheme for measuring the node-to-ground distance (© S. Ramm)

Based on experience gained during the second experimental year, the pre-harvest assessment was further expanded. Starting from the third experimental year, measurement of soil surface conditions was also included in the pre-harvest assessment.

With the adaptation of the measurement scheme for assessing soil surface conditions (Figure 4) and the introduction of the node-to-ground distance measurement (Figure 5) from the second experimental year onward, it became possible to derive an additional parameter based on the plot mean values of these two measurements. The node-to-lowest-working-plane distance describes the vertical distance between the lowest node of the corn plant and the lowest possible working plane of the shredding tools of the HS3 or flail mowers without making contact with the soil (Figure 6). Two different scenarios must be considered:

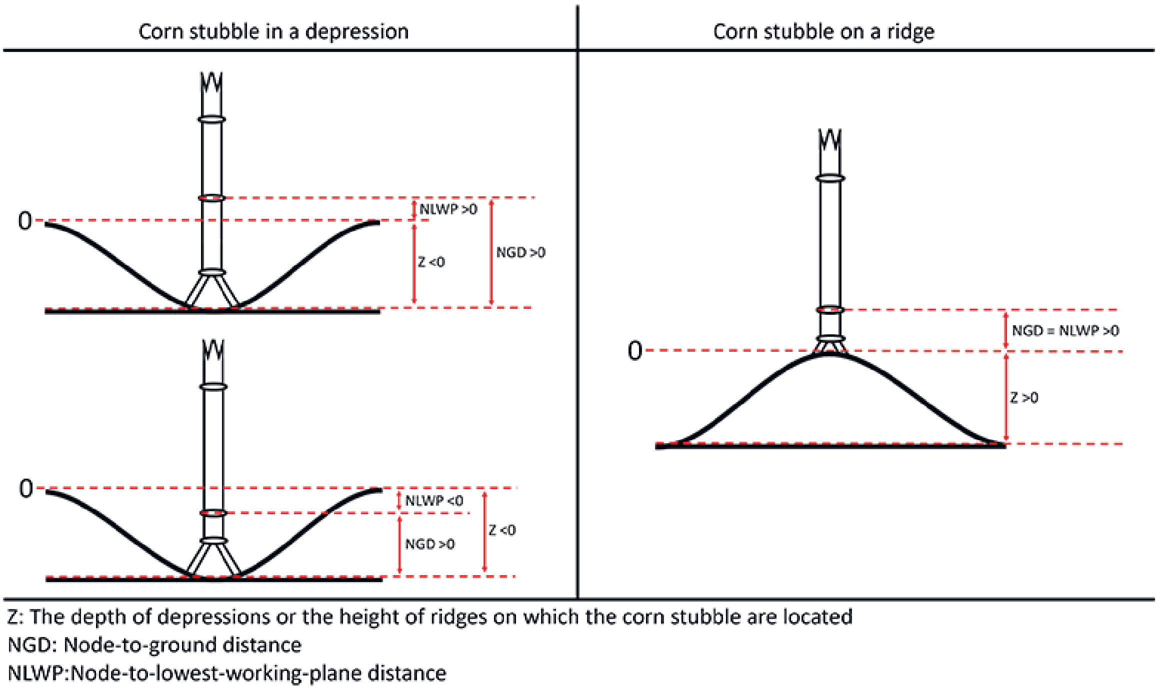


Figure 6: Schematic representation of the node-to-lowest-working-plane distance under two conditions: (Left) corn stubble located in a depression; the measured node-to-ground distance plus the depression depth defines whether the lowest node lies above (positive) or below (negative) the reachable working plane of the shredding tools. (Right) corn stubble located on a ridge; the node-to-ground distance equals the node-to-lowest-working-plane distance and is always positive.

1) Corn stubble located in depressions: By adding the measured depression depth (negative values) to the node-to-ground distance, the resulting value represents the node-to-lowest-working-plane distance. A positive value indicates that the shredding tools of the HS3 or the flail mower are potentially able to reach the lowest node of the corn plant without soil contact (Figure 6, top left). A negative value means that the lowest node lies below the lowest possible working height of the tools, making it inaccessible without soil contact (Figure 6, bottom left).
2) Corn stubble located on ridges: In this case, the node-to-ground distance is equal to the node-to-lowest-working-plane distance. Only positive values are possible (Figure 6, right).

Results

As outlined in the Materials and Methods section, the methodological approach was continuously refined over the course of the study. Considering this development, the Results section presents not only the findings of the data collection, but also highlights insights gained during the trials that led to subsequent methodological adjustments. Accordingly, the structure of the Results section is primarily organized by experimental year. The section concludes with a comprehensive evaluation covering the second to fourth experimental years, focusing on the combined influence of soil surface conditions and node-to-ground distance, expressed as the node-to-lowest-working-plane distance, on corn stubble shredding intensity.

Findings from the first year of field trials

The soil surface conditions at the Zeutern site appeared to provide favorable conditions for effective corn stubble shredding (Table 4). The assessment results from Zeutern show variation across all rating levels. On average, 20.0% of the corn stubble stood on ridges (Level 1), 51.7% on a level surface (Level 2), and 28.3% in depressions (Level 3). No clear trend was observed across repetitions, suggesting that the soil surface was predominantly level. The conditions at the Steinheim site, however, were different. On average, 87.5% of the corn stubble stood in depressions (Level 3), which appears to have influenced the intensity of stubble shredding.

Table 4: Soil surface conditions at the Zeutern and Steinheim sites (first year of field trials), relative frequencies per rating level in the two-step method treatment (HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower) plots

Site	Block	N[1)]	Rating level of soil surface condition in %[2)]		
			1	2	3
Zeutern (2018)	A	40	27.5	47.5	25.0
	B	40	22.5	35.0	42.5
	C	40	10.0	72.5	17.5
	Mean		20.0	51.7	28.3
Steinheim (2018)	A	24	8.3	12.5	79.2
	B	24	0.0	16.7	83.3
	C	24	0.0	0.0	100.0
	Mean		2.8	9.7	87.5

[1)] N = sample size. [2)] Level 1: corn stubble standing on ridges; Level 2: on a level surface; Level 3: in depressions.

With an average of 86.7% of corn stubble completely destroyed (Level 1) in the single-step method treatment at the Zeutern site, the newly developed HS3, equipped with flail knives, achieved a result comparable to the flail mower used in the two-step method treatment in terms of corn stubble shredding intensity (Table 5). In the single-step method treatment, the proportion of completely destroyed corn stubble varied from 78,0% to 100,0% (Table A1 in the Appendix). In the two-step method treatment, the proportion ranged from 78.0% to 98.0%, averaging 87.3% (Table A2 in the Appendix). In the control treatment, as expected, the highest proportion of intact corn stubble remained, with 86.0% retaining at least one undamaged internode (Level 5). As described in Material and Methods section, overrun stubble could not be evaluated at the Zeutern site due to the specific combine harvester model used.

At the Steinheim site, only 54.4% of the non-overrun corn stubble in the single-step method treatment were completely destroyed on average (Level 1), while 35.6% retained at least one intact internode corresponding to rating level 5 (Table 5). Similarly, in the two-step method treatment, the intensity of stubble shredding was significantly lower compared to the Zeutern site, with 51.7% of non-overrun corn stubble being fully destroyed (Level 1) and 35.0% retaining an intact internode (Level 5).

Table 5: Corn stubble shredding intensity at the Zeutern and Steinheim sites (first year of field trials), mean relative frequencies per rating level

Site	Treatment[1)]	Non-overrun stubble				Overrun stubble			
		N[2)]	Level of corn stubble shredding in %[3)]			N[2)]	Level of corn stubble shredding in %[3)]		
			1	2–4	5		1	2–4	5
Zeutern (2018)[4)]	Single-step method	150	86.7	9.3	4.0	n.e.	n.e.	n.e.	n.e.
	Two-step method	150	87.3	4.0	8.7	n.e.	n.e.	n.e.	n.e.
	Control	150	0.7	13.3	86.0	n.e.	n.e.	n.e.	n.e.
Steinheim (2018)[5)]	Single-step method	90	54.4	10.0	35.6	90	61.1	8.9	30.0
	Two-step method	60	51.7	13.3	35.0	60	48.3	11.7	40.0
	Control	90	0.0	0.0	100.0	90	10.0	28.9	61.1

[1)] Single-step method: HS3 corn header equipped with flail knives, operating at the lowest possible cutting height; Two-step method: HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower; Control: HS3 corn header with standard knives at a cutting height of 15–25 cm, no additional corn stubble treatment.
[2)] N = sample size.
[3)] Level 1: completely destroyed; Level 2-4: damaged; Level 5: intact corn stubble.
[4)] As described in the Materials and Methods section, due to the specific combine harvester model used at the Zeutern site, no corn stubble was overrun (n.e.: not evaluated).
[5)] For mean value calculations in the two-step method treatment, block B was excluded.

For the calculation of mean values in the two-step method treatment, Block B was excluded at Steinheim site. In this repetition, the flail mower was inadvertently operated in the same direction as the harvest instead of in the opposite direction, which is known to reduce its working quality (Grosa et al. 2016). It is likely that these circumstances contributed to the low intensity of stubble shredding (Table A2 in the Appendix) and the increased height of the solid corn stubble segments (Table A9 in the Appendix) in this plot.

The crushing of corn stubble due to being overrun by the combine harvester's tracks and tires was evident in the control treatment at the Steinheim site. On average, 28.9% of the evaluated corn stubble was classified as Level 2–4 (Table 5), with 21.3% specifically categorized as Level 3 (Table A2 in the Appendix), indicating laterally split or crushed stubble. Given the already poor working quality observed in both the single-step method and two-step method treatments, no clear effect of stubble being overrun by the combine harvester on corn stubble shredding intensity was detected in either treatment.

The solid segment heights of corn stubble presented in Table 6 generally align with the results of the corn stubble shredding intensity assessment. The shorter the corn stubble, the higher the proportion of completely destroyed stubble.

Table 6: Mean and standard deviation of the solid corn stubble segment height at the Zeutern and Steinheim sites (first year of field trials)

Site	Treatment[1)]	Non-overrun stubble		Overrun stubble	
		N[2)]	Solid stubble height in cm (mean ± SD)	N[2)]	Solid stubble height in cm (mean ± SD)
Zeutern (2018)[3)]	Single-step method	150	2.8 ± 2.3	n.e.	n.e.
	Two-step method	150	5.1 ± 4.9	n.e.	n.e.
	Control	150	17.0 ± 3.5	n.e.	n.e.
Steinheim (2018)[4)]	Single-step method	90	5.5 ± 6.2	90	4.4 ± 4.5
	Two-step method	60	4.0 ± 2.9	60	6.2 ± 4.3
	Control	90	22.1 ± 1.9	90	22.9 ± 2.7

[1)] Single-step method: HS3 corn header equipped with flail knives, operating at the lowest possible cutting height; Two-step method: HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower; Control: HS3 corn header with standard knives at a cutting height of 15–25 cm, no additional corn stubble treatment.
[2)] N = sample size.
[3)] As described in the Materials and Methods section, due to the specific combine harvester model used at the Zeutern site, no corn stubble was overrun (n.e.: not evaluated).
[4)] For mean value calculations in the two-step method treatment, block B was excluded.

However, at the Steinheim site, the corn stubble in the two-step method treatment was shorter, despite the flail mower achieving lower shredding intensities compared to the Zeutern site. While the results are not directly comparable due to the use of different flail mower models, they are consistent with a frequently observed stubble pattern at the Steinheim site (Figure 7). Corn stubble with short intact internodes were standing in depressions. Apparently, the flail knives of the HS3 in the single-step method treatment, as well as the tools of the flail mower in the two-step method treatment, were unable to reach the stubble sufficiently close to the soil surface. As a result, the shredding of the corn stubble was halted at the node. This underscores the significant influence of soil surface conditions, particularly in interaction with the position of the lower node of the corn plant, on the intensity of corn stubble shredding. For comparison, Figure A1 in the Appendix provides an exemplary illustration of the intended stubble pattern for each treatment.

Figure 7: Typical stubble pattern at the Steinheim site (first year of field trials; © S. Ramm)

Consequently, the methods were refined for the second experimental year, as described in the Material and Methods section: (1) the number of replications was increased to six, (2) a pre-harvest assessment was introduced to measure the node-to-ground distance, (3) the assessment of soil surface conditions was replaced with a measurement of depression depth and ridge height, which was conducted alongside the evaluation of corn stubble shredding intensity in all treatments, and (4) in addition to measuring the height of the solid segment of the corn stubble, the total stubble height was also recorded.

Findings from the second year of field trials

Pre-harvest measurements of the node-to-ground distance in the standing crop at the Bückeburg and Stettfeld sites revealed large differences between the experimental sites. At Bückeburg, the node-to-ground distance was approximately twice as large as at the Stettfeld site (Table 7).

Table 7: Node-to-ground distance at the Bückeburg and Stettfeld sites (second year of field trials)

Site	Treatment[1)]	N[2)]	Node-to-ground distance in cm (mean ± SD)
Bückeburg (2019)	Single-step method	150	10.0 ± 3.3
	Two-step method	150	10.4 ± 3.1
	Control	150	10.4 ± 2.9
Stettfeld (2019)	Single-step method	240	5.3 ± 1.5
	Two-step method	240	4.9 ± 1.7
	Control	240	5.0 ± 1.6

[1)] Single-step method: HS3 corn header equipped with flail knives, operating at the lowest possible cutting height; Two-step method: HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower; Control: HS3 corn header with standard knives at a cutting height of 15–25 cm, no additional corn stubble treatment.

[2)] N = sample size.

In comparison between the two sites, Bückeburg not only had a node-to-ground distance nearly twice as large as Stettfeld, but also a significantly smoother soil surface. In the single-step method and control treatment, corn stubble in non-overrun areas stood, on average, in −1.9 cm deep depressions. In contrast, at the Stettfeld site, the depressions were nearly twice as deep, measuring −4.0 and −3.9 cm, respectively (Table 8). Hence, the conditions at the Bückeburg site were considerably better for corn stubble shredding.

A comparison between non-overrun and overrun areas further indicates that, at the Bückeburg site, the single-step method and control treatment exhibited an approximately 2 cm greater distance between the reference bar and the soil surface in areas where corn stubble had been overrun by the combine harvester (Table 8). This effect was not observed at the Stettfeld site, indicating that the combine harvester's tracks and tires did not create deep ruts.

Table 8: Post stubble treatment soil surface condition assessment for overrun and non-overrun corn stubble at the Bückeburg, and Stettfeld sites (second year of field trials)

Site	Treatment[1)]	Non-overrun stubble		Overrun stubble	
		N[2)]	Soil surface condition in cm (mean ± SD)	N[2)]	Soil surface condition in cm (mean ± SD)
Bückeburg (2019)	Single-step method	160	−1.9 ± 0.8	160	−4.1 ± 1.2
	Two-step method	160	−0.6 ± 1.9	160	−3.4 ± 1.3
	Control	160	−1.9 ± 1.1	160	−4.2 ± 1.2
Stettfeld (2019)	Single-step method	240	−4.0 ± 1.4	240	−3.6 ± 1.4
	Two-step method	240	−2.8 ± 1.3	240	−3.6 ± 1.3
	Control	240	−3.9 ± 1.7	240	−3.9 ± 1.9

1) Single-step method: HS3 corn header equipped with flail knives, operating at the lowest possible cutting height; Two-step method: HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower; Control: HS3 corn header with standard knives at a cutting height of 15–25 cm, no additional corn stubble treatment.
2) N = sample size.

Notably, at the Bückeburg site, depressions in the two-step method treatment were shallower both inside and outside the combine harvester's track zones compared to the single-step method and control treatment. A similar pattern was observed in non-overrun areas at the Stettfeld site, likely due to the leveling effect of the support rollers off the flail mowers. This effect compromises the interpretability of the measurements for the two-step method treatment. Consequently, starting from the third experimental year, the assessment of soil surface conditions was also conducted before harvest in the standing corn crop, alongside the node-to-ground distance.

The favorable conditions at the Bückeburg site are reflected in the results of the corn stubble shredding intensity assessment (Table 9). Both corn stubble treatments achieved a high intensity of shredding for stubble that had not been overrun by the combine harvester's tracks and tires. In the single-step method, an average of 88.8% of the corn stubble was completely destroyed (Level 1), while only 7.5% remained intact (Level 5). Similarly, in the two-step method, 84.5% of the corn stubble was fully shredded (Level 1), with 11.0% remaining intact (Level 5), yielding comparable results. The advantage of the single-step method becomes evident in the combine harvester's track zones. The flail mower in the two-step method treatment completely destroyed only 11.5% of the overrun corn stubble, while 56.5% retained at least one intact internode—only slightly better than the results observed in the control treatment without stubble processing. The newly developed HS3, equipped with flail knives, is inherently unaffected by this limitation. In the single-step method treatment, an average of 95.4% of the overrun corn stubble was completely destroyed, with only 2.9% remaining intact. This suggests that the crushing effect of the combine harvester's tracks and tires may have further enhanced the intensity of stubble fragmentation, particularly when applied to the short stubble processed by the HS3 equipped with flail knives.

In the two-step method at the Bückeburg site, a clearly deviant rating was observed in block E. This value was excluded from the calculation of the means. The same applies to the calculation of the mean stubble height (Table 10). The cause could not be determined conclusively. It is presumed that the flail mower was not fully lowered.

Table 9: Corn stubble shredding intensity at the Bückeburg and Stettfeld sites (second year of field trials), mean relative frequencies per rating level

Site	Treatment[1)]	Non-overrun stubble				Overrun stubble			
		N[2)]	Level of corn stubble shredding in %[3)]			N[2)]	Level of corn stubble shredding in %[3)]		
			1	2–4	5		1	2–4	5
Bückeburg (2019)[4)]	Single-step method	160	88.8	3.8	7.5	160	95.4	1.7	2.9
	Two-step method	140	84.5	4.5	11.0	140	11.5	32.0	56.5
	Control	160	0.0	11.3	88.8	160	4.2	35.0	60.8
Stettfeld (2019)[5)]	Two-step method	240	45.0	42.1	12.9	240	11.3	14.2	74.6
	Control	240	0.4	1.3	98.3	240	17.5	8.3	74.2

[1)] Single-step method: HS3 corn header equipped with flail knives, operating at the lowest possible cutting height; Two-step method: HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower; Control: HS3 corn header with standard knives at a cutting height of 15–25 cm, no additional corn stubble treatment.
[2)] N = sample size.
[3)] Level 1: completely destroyed; Level 2-4: damaged; Level 5: intact corn stubble.
[4)] Block E was excluded from the two-step method treatment as outlier.
[5)] As described in the Materials and Methods section, no results are available for the single-step method treatment due to a malfunction of the header height control system.

At the Stettfeld site, the less favorable conditions are evident in the two-step method treatment. The flail mower was able to fully destroy only 45.0% of the non-overrun corn stubble (Level 1). However, the majority of the corn stubble was at least damaged, with only 12.9% classified as rating level 5. As described in the Materials and Methods section, no results are available for the single-step method treatment due to a malfunction of the header height control system.

The assessment of overrun corn stubble confirms observations from the Bückeburg site, showing that the flail mower was unable to effectively process the flattened stubble. An average of 74.6% of the overrun stubble were classified as rating level 5, indicating that these stubble retained an intact internode. A comparison with the control treatment reveals that, at this experimental site, flail mowing had no measurable effect on the overrun corn stubble (Table 9). This finding is further supported by the measured corn stubble heights (Table 10). In general, the average total heights and solid segment heights of the corn stubble align with the results of the assessment of corn stubble shredding intensity from both sites, showing the same ranking of treatments and the treatment-dependent effect of stubble overrunning (Table 10).

Table 10: Total corn stubble height and solid stubble segment height at the Bückeburg and Stettfeld sites (second year of field trials), mean and standard deviation

Site	Treatment 1)	Non-overrun stubble			Overrun stubble		
		N 2)	Corn stubble height in cm		N 2)	Corn stubble height in cm	
			Total	Solid		Total	Solid
Bückeburg (2019) 3)	Single-step method	160	6.7 ± 2.5	0.6 ± 1.9	160	5.2 ± 2.9	0.2 ±1 .2
	Two-step method	140	7.8 ± 2.0	1.1 ± 2.8	140	15.2 ± 3.5	12.6 ± 6.5
	Control	160	14.9 ± 1.8	14.9 ± 1.8	160	17.0 ± 2.5	15.0 ± 5.3
Stettfeld (2019) 4)	Two-step method	240	6.5 ± 3.0	2.8 ± 2.8	240	14.5 ± 3.2	10.5 ± 6.1
	Control	240	16.0 ± 1.9	15.8 ± 3.5	240	14.9 ± 2.5	10.0 ± 7.1

1) Single-step method: HS3 corn header equipped with flail knives, operating at the lowest possible cutting height; Two-step method: HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower; Control: HS3 corn header with standard knives at a cutting height of 15–25 cm, no additional corn stubble treatment.
2) N = sample size.
3) Block E was excluded from the two-step method treatment as outlier.
4) As described in the Materials and Methods section, no results are available for the single-step method treatment due to a malfunction of the header height control system.

Findings from the third and fourth year of field trials

Differences in the node-to-ground distance were also observed in the third and fourth experimental years. At the northern German experimental sites, Timmaspe and Wöbs, the average distances ranged between 8.0 and 8.3 cm. In contrast, at the southern German experimental site, the distances were lower, averaging 6.1 to 6.5 cm (Table 11).

Table 11: Node-to-ground distance at the Kraichtal, Timmaspe and Wöbs sites (third and fourth year of field trials)

Site	Treatment 1)	N 2)	Node-to-ground distance in cm (mean ± SD)
Kraichtal (2020)	Single-step method	240	6.5 ± 2.4
	Two-step method	240	6.1 ± 2.2
	Control	240	6.2 ± 2.4
Timmaspe (2020) 3)	Single-step method	200	8.3 ± 3.1
	Two-step method and Control	200	8.0 ± 2.8
Wöbs (2021)	Single-step method	240	8.3 ± 2.5
	Two-step method	240	8.3 ± 2.7
	Control	240	8.3 ± 2.6

1) Single-step method: HS3 corn header equipped with flail knives, operating at the lowest possible cutting height; Two-step method: HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower; Control: HS3 corn header with standard knives at a cutting height of 15–25 cm, no additional corn stubble treatment.
2) N = sample size.
3) The control and two-step method treatments were assessed sequentially in the same plots.

Starting from the third experimental year, the measurements assessing soil surface conditions were conducted not only after the corn stubble treatment but also before harvest in the standing corn crop, alongside the measurements of the node-to-ground distance. Table 12 presents the mean values of these measurements for the three sites, categorized by treatment.

Notably, across all sites and treatments, a smoother soil surface was observed after stubble treatment, as indicated by higher measured values compared to pre-harvest measurements in the standing corn crop. This suggests systematic underestimation in post-treatment assessments. Potential causes include not only the direct impact of the machinery but also the need to clear away corn stover lying on the soil surface before conducting the post-treatment measurements.

Although the node-to-ground distances were relatively small at the Kraichtal site, the exceptionally level soil surface provided favorable conditions for stubble shredding (Table 12). While the node-to-ground distances at Timmaspe and Wöbs were similar, the sites differed in terms of soil surface conditions. According to the newly introduced pre-harvest soil surface assessment, the average depression depth was measured at −4.0 cm at the Timmaspe site, compared to −2.3 and −2.5 cm at the Wöbs site. This indicates that soil conditions at the Wöbs site were more conducive to effective stubble shredding.

Table 12: Pre-harvest and post stubble treatment soil surface condition assessment for overrun and non-overrun corn stubble at the Kraichtal, Timmaspe, and Wöbs sites (third and fourth year of field trials)

Site	Treatment[1)]	Pre-harvest		Post stubble treatment			
				Non-overrun stubble		Overrun stubble	
		N[2)]	Soil surface condition in cm (mean ± SD)	N[2)]	Soil surface condition in cm (mean ± SD)	N[2)]	Soil surface condition in cm (mean ± SD)
Kraichtal (2020)	Single-step method	240	−0.9 ± 1.2	120	−0.4 ± 1.7	120	−0.4 ± 1.3
	Two-step method	240	−0.5 ± 1.2	120	0.7 ± 1.0	120	−0.1 ± 1.2
	Control	240	−0.7 ± 1.1	120	0.6 ± 1.3	120	−0.2 ± 1.3
Timmaspe (2020)[3)]	Single-step method	200	−4.0 ± 1.5	100	−3.0 ± 1.1	100	−4.3 ± 1.4
	Two-step method	200	−4.0 ± 1.4	100	−1.9 ± 1.2	100	−2.7 ± 1.4
	Control	200	−4.0 ± 1.4	100	−2.8 ± 0.9	100	−4.5 ± 1.1
Wöbs (2021)[4)]	Single-step method	240	−2.4 ± 0.9	120	−0.5 ± 1.5	120	−3.6 ± 1.19
	Two-step method	240	−2.5 ± 1.0	n.e.	n.e.	n.e.	n.e.
	Control	240	−2.3 ± 0.9	120	−1.5 ± 1.3	120	−3.3 ± 1.4

1) Single-step method: HS3 corn header equipped with flail knives, operating at the lowest possible cutting height; Two-step method: HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower; Control: HS3 corn header with standard knives at a cutting height of 15–25 cm, no additional corn stubble treatment.
2) N = sample size.
3) The control and two-step method treatments were assessed sequentially in the same plots.
4) Due to snowfall, no measurements were available for the two-step method treatment after harvest (n.e.: not evaluated).

These findings are reflected in the results of the corn stubble shredding intensity assessment for non-overrun corn stubble in the single-step method treatment (Table 13). At the Timmaspe site, the HS3 equipped with flail knives achieved, on average, only 37.0% complete corn stubble destruction (Level 1), while 46.0% of the stubble remained with an intact internode. In contrast, results at the Wöbs site were better, though still not optimal: 73.0% of the corn stubble were completely destroyed (Level 1) in the single-step method, 16.0% showed partial damage (Level 2-4), and 11.0% remained with an undamaged internode (Level 5). The two-step method treatment at the Timmaspe site appeared to be less affected by the challenging conditions (Table 13). The flail mower was able to completely destroy 76.0% of the non-overrun corn stubble (Level 1), while 22.0% of the stubble remained with an intact internode (Level 5).

At the Kraichtal site, the flail mower achieved excellent results in the two-step method treatment, with 87.5% of the non-overrun corn stubble fully destroyed (Level 1) and 11.7% remaining with an intact internode (Level 5). In contrast, the HS3 equipped with flail knives yielded highly variable results in the single-step method treatment at the Kraichtal site (Table 13). Across repetitions B to F, the proportion of completely destroyed non-overrun corn stubble (Level 1) ranged from 45.0% to 80.0%, while the proportion of stubble with an intact internode (Level 5) varied between 10.0% and 40.0%. Repetition A was considered an outlier and excluded from the analysis, as 95.0% of the corn stubble remained with an intact internode (Level 5), and no corn stubble was fully destroyed (Table A5 in the Appendix). Plot A of the single-step method treatment had an average slope of 8.2° perpendicular to the combine harvester's driving direction (based on a 1 × 1 m digital terrain model). It is possible that the HS3, as a row-dependent implement, was unable to properly reach the corn stubble due to the lateral inclination of the terrain.

Table 13: Corn stubble shredding intensity at the Kraichtal, Timmaspe and Wöbs sites, mean relative frequencies per rating level (third and fourth year of field trials)

Site	Treatment[1)]	Non-overrun stubble N[2)]	Non-overrun: Level of corn stubble shredding in %[3)]			Overrun stubble N[2)]	Overrun: Level of corn stubble shredding in %[3)]		
			1	2-4	5		1	2-4	5
Kraichtal (2020)[4)]	Single-step method	100	64.0	13.0	23.0	100	87.0	2.0	11.0
	Two-step method	120	87.5	0.8	11.7	120	44.2	10.8	45.0
	Control	120	0.8	5.0	94.2	120	35.0	12.5	52.5
Timmaspe (2020)[5)]	Single-step method	100	37.0	17.0	46.0	100	67.0	5.0	28.0
	Two-step method	100	76.0	2.0	22.0	100	36.0	20.0	44.0
	Control	100	0.0	3.0	97.0	100	39.0	12.0	49.0
Wöbs (2021)[6,7)]	Single-step method	100	73.0	16.0	11.0	100	94.0	2.0	4.0
	Control	120	0.8	0.0	99.2	120	24.2	20.8	55.0

1) Single-step method: HS3 corn header equipped with flail knives, operating at the lowest possible cutting height; Two-step method: HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower; Control: HS3 corn header with standard knives at a cutting height of 15–25 cm, no additional corn stubble treatment.
2) N = sample size.
3) Level 1: completely destroyed; Level 2-4: damaged; Level 5: intact corn stubble.
4) Due to an outlier in Repetition A of the single-step method treatment, only five repetitions were included in the calculation of the mean.
5) The control and two-step method treatments were assessed sequentially in the same plots.
6) Due to snowfall, no measurements are available for the two-step method treatment.
7) Due to an outlier in Repetition C of the single-step method treatment, only five repetitions were included in the calculation of the mean.

A comparison of the two-step method treatment results for non-overrun and overrun stubble at the Kraichtal and Timmaspe sites highlights the significant impact of corn stubble overrun on the shredding intensity of the flail mowers (Table 13). At both sites, the number of fully destroyed corn stubble within the combine harvester's wheel and track paths were approximately halved compared to non-overrun stubble. Simultaneously, the proportion of stubble with an intact internode increased dramatically. As previously noted, the HS3 equipped with flail knives is not affected by this effect. On the contrary, at all three sites, the proportion of fully destroyed corn stubble was significantly higher in the wheel tracks of the combine harvester, while the proportion of intact stubble was substantially reduced. This suggests that the overrunning of already shortened corn stubble contributes to this effect.

Table 14 confirms that the findings from the corn stubble shredding intensity assessment are consistently reflected in the measured stubble heights. In particular, the comparison of total stubble height and the height of the solid stubble segment between the single-step and two-step method treatments at the Kraichtal and Timmaspe sites illustrates that even small differences in cutting height can have a significant impact on corn stubble shredding intensity.

Table 14: Total corn stubble height and solid stubble segment height at the Kraichtal, Timmaspe, and Wöbs sites, mean and standard deviation (third and fourth year of field trials)

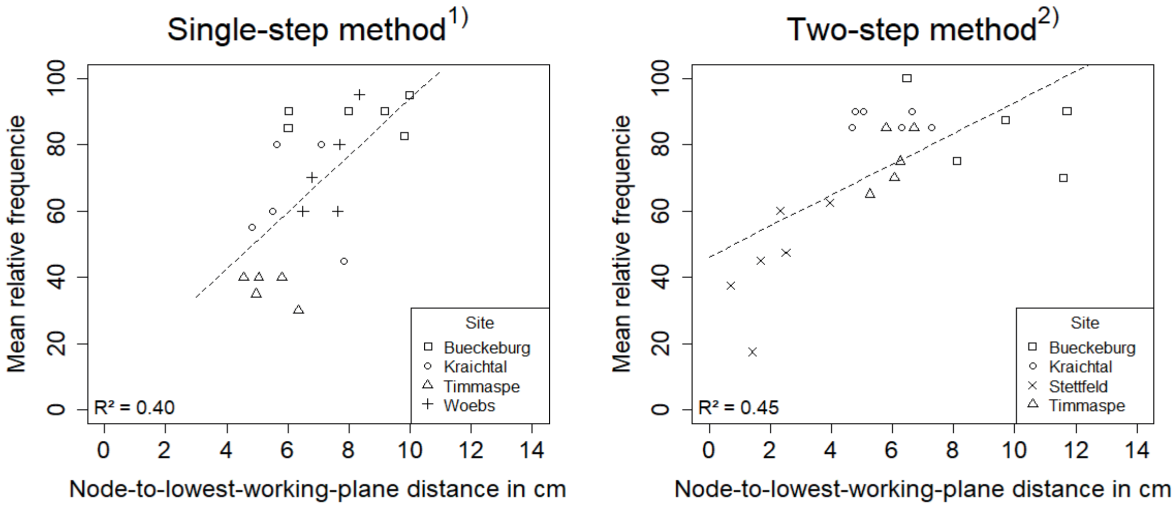
Site	Treatment[1)]	Non-overrun stubble			Overrun stubble		
		N[2)]	Corn stubble height in cm		N[2)]	Corn stubble height in cm	
			Total	Solid		Total	Solid
Kraichtal (2020)[3)]	Single-step method	100	8.0 ± 2.2	4.3 ± 2.4	100	6.1 ± 2.4	2.0 ± 2.0
	Two-step method	120	7.5 ± 2.1	3.1 ± 2.3	120	9.9 ± 3.3	5.9 ± 4.4
	Control	120	12.6 ± 1.2	12.4 ± 1.6	120	11.5 ± 2.5	6.7 ± 4.8
Timmaspe (2020)[4)]	Single-step method	100	10.5 ± 3.0	6.6 ± 3.8	100	11.1 ± 3.5	3.9 ± 3.3
	Two-step method	100	10.0 ± 2.9	3.4 ± 3.2	100	16.2 ± 4.1	9.6 ± 7.3
	Control	100	17.9 ± 2.4	17.5 ± 2.7	100	18.2 ± 2.4	9.3 ± 7.2
Wöbs (2021)[5,6)]	Single-step method	100	5.8 ± 2.3	3.7 ± 2.2	100	4.9 ± 2.6	2.1 ± 1.5
	Control	120	21.3 ± 2.5	20.7 ± 2.7	120	21.0 ± 4.4	12.3 ± 8.0

1) Single-step method: HS3 corn header equipped with flail knives, operating at the lowest possible cutting height; Two-step method: HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower; Control: HS3 corn header with standard knives at a cutting height of 15–25 cm, no additional corn stubble treatment.
2) N = sample size.
3) Due to an outlier in Repetition A of the single-step method treatment, only five repetitions were included in the calculation of the mean.
4) The control and two-step method treatments were assessed sequentially in the same plots.
5) Due to snowfall, no measurements are available for the two-step method treatment.
6) Due to an outlier in Repetition C of the single-step method treatment, only five repetitions were included in the calculation of the mean.

Influence of soil surface conditions and node-to-ground distance on corn stubble shredding intensity, based on data from the second to fourth year of field trails

In the preceding chapters, soil surface condition and node-to-ground distance were identified as key factors influencing corn stubble shredding intensity. This relationship is particularly important considering the observation that nodes positioned below the working plane of the shredding tools can halter the shredding of the corn stubble (Figure 7). It became evident that the combination of low node-to-ground distances and corn stubble standing in deep depressions significantly reduces shredding intensity. This is typically reflected in a lower relative frequency of completely destroyed corn stubble (Level 1). As described in the Materials and Methods section, the interaction between these two factors can be expressed through the derived parameter node-to-lowest-working-plane distance (Figure 6). This metric represents the vertical distance between the lowest node of the corn plant and the lowest possible working plane of the shredding tools without soil contact. The trend depicted in Figure 8 supports these findings. It illustrates the relationship between node-to-lowest-working-plane distance and the relative frequency of totally destroyed corn stubble (Level 1), based on plot means for the single-step and two-step method treatments, considering only non-overrun corn stubble. An increase in node-to-lowest-working-plane distance generally results in a higher frequency of completely destroyed corn stubble (Level 1).

For the calculation of the node-to-lowest-working-plane distance, data from the post-harvest assessments of soil surface conditions were used. As previously mentioned, depression depths tend to



1) HS3 corn header equipped with flail knives, operating at the lowest possible cutting height; At the Kraichtal site, block A, and at the Wöbs site, block C were excluded as outliers.

2) HS3 corn header equipped with standard knives at a cutting height of 15–25 cm, followed by a tractor-driven flail mower; at the Bückeburg site, block E was excluded as an outlier.

Figure 8: Relative frequencies of totally destroyed corn stubble (Level 1) as a function of node-to-lowest-working-plane distance for non-overrun corn stubble. Left: Single-step method treatment at the Bückeburg (second year of field trails), Kraichtal and Timmaspe (third year of field trails), and Wöbs (fourth year of field trails) sites. Right: Two-step method treatment at the Bückeburg and Stettfeld (second year of field trails), as well as Kraichtal and Timmaspe (third year of field trails) sites. Values are based on plot means.

be systematically underestimated in post-harvest measurements, which should be taken into account when interpreting the results. In the case of the two-step method treatment, it must also be considered that the measurements may have been affected by the leveling effect of the flail mower's support rollers. Moreover, different flail mower models were used at the various sites, which could further influence the comparability of results.

Discussion

Experimental approach and methods for assessing corn stubble shredding intensity

The implementation of the field trials as randomized complete block designs in the form of on-farm experiments proved to be both appropriate and feasible. In light of the considerable variation in the corn stubble shredding intensity ratings within individual sites, the decision to double the number of replications to six from the second experimental year onward was justified. This variation was not limited to a specific corn stubble treatment but occurred across both the single-step method (Table A5 in the Appendix) and the two-step method (Table A3 in the Appendix). The reduction in plot length to 75 m, which was introduced in conjunction with the increased number of replications, also proved sufficient for reliable data collection. However, it should be noted that such field trials are time-intensive, especially when additional analyses such as corn stover sampling are included (cf. Ramm et al. 2024). Planning must also account for weather-related uncertainties during grain corn harvest in Germany.

Originally developed as a decision-support tool for farmers regarding the use of flail mowers, the rating system proposed by Brunotte and Vosshenrich (2017) has proven to be a suitable starting point for further developing scientific methods for assessing corn stubble shredding performance. In particular, the five-level rating scale enables a detailed classification of corn stubble according to the degree of shredding intensity (Table 3). While in most cases a simplified grouping into intact (Level 5), damaged (Levels 2–4), and fully destroyed stubble (Level 1) is sufficient, the finer differentiation within Levels 2 to 4 provides valuable insights into the mechanisms of action, such as the crushing effect caused by overrunning the stubble. Moreover, this intermediate range would likely become more relevant if the study were extended to include not only actively driven implements, but also passive devices such as crimping rollers.

Another valuable and easily measurable indicator is the total height of the remaining corn stubble. However, this parameter alone is insufficient for assessing shredding intensity. A more informative approach is to also measure the height of the solid stubble segment, as this reveals how much of the stalk was effectively shredded by the implement. For instance, at the Bückeburg site, the flail knives of the HS3 in the single-step method treatment shredded an average of 6.1 cm of the corn stubble (Table 10), whereas at the Timmaspe site only 3.9 cm were shredded (Table 13). This highlights the importance of recording both total corn stubble heights and solid segment heights. Furthermore, the shredding depth below the cutting height likely depends strongly on both the design of the shredding tool and site-specific conditions, especially the soil surface condition and the node-to-ground distance.

Determinants of corn stubble shredding intensity

With regard to site-specific conditions, the methods originally proposed by Brunotte and Vosshenrich (2017) proved insufficient for research applications. The sole assessment of soil surface conditions using the three-level rating system, differentiating between stubble standing on ridges (Level 1), on a level surface (Level 2), and in depressions (Level 3) (Figure 3), did not provide the level of precision required for a scientific evaluation. The measurement approach introduced in the second experimental year, using an aluminum reference bar placed across the rows as a fixed reference point, proved to be a more robust method for quantifying soil surface variation (Figure 4). However, as described before, it is recommended that this measurement be conducted prior to harvest in the standing crop, together with the assessment of node-to-ground distance, to avoid any potential influence from the implements used. This approach was adopted starting from the third experimental year (Table 13).

As a complementary or alternative approach, it may also be worth considering a further adaptation of the soil surface condition measurement method. Instead of limiting the reference bar to a single corn row, it could be extended across the entire working width of the stubble shredding implement. This would be particularly relevant for implements with a rigid frame, where the highest points within the working width determine the implement‘s effective cutting height. In this approach, all corn stalks aligned along a single cross-section of the implement’s working width should be included in the measurement. For example, in the case of the HS3, which has a working width of 6 m and a row spacing of 75 cm, this would correspond to eight rows of corn plants being assessed simultaneously. However, implementing this method in the standing crop is likely to be challenging. In practice, it may require the removal of selected plants to make it possible to position such a wide reference bar across multiple rows. Despite these logistical constraints, this approach would provide a more comprehensive representation of the actual working conditions faced by full-width implements.

The combination of soil surface condition and node-to-ground distance, expressed as the parameter node-to-lowest-working-plane distance, emerged as a key influencing factor for corn stubble shredding intensity (Figure 8). The lower the node-to-ground distance and the deeper the depression in which the stubble stands, i.e., low node-to-lowest-working-plane distance, the more difficult it becomes to achieve sufficient shredding performance. The investigations have shown that these parameters can vary significantly between sites, with node-to-ground distances ranging from 4.9 cm at the Stettfeld site to 10.4 cm at the Bückeburg site (Table 7), and soil surface condition measurements ranging from −4.0 cm at Stettfeld site (Table 8) to 0.7 cm at Kraichtal site (Table 12). For this reason, recording this site-specific parameters is strongly recommended in future studies.

Considerations for refining data collection in future studies

In the present study, pre-harvest and post-harvest assessments were conducted on different corn stubble, which limited the analysis to plot mean values. Establishing a consistent dataset at the individual corn stubble level would allow for a more detailed and statistically robust evaluation of the relationships between shredding intensity and influencing variables. To achieve this, it would be necessary to mark specific corn stubble before harvest and relocate them after stubble treatment. While this approach may be challenging due to the thick layer of plant residue left on the field, it offers the potential for significantly more precise and comprehensive data analysis.

As described in the Material and Method section, internodes shorter than 3 cm were excluded from both the assessment of corn stubble shredding intensity and the measurement of node-to-ground distance, based on the assumption that this length is insufficient to accommodate overwintering European corn borer (ECB) larvae. However, this exclusion was not solely based on space requirements. In practice, it was observed that none of the tested corn stubble shredding implements were able to effectively process these extremely short internodes. Consequently, including these internodes in the evaluation would have obscured treatment differences, as none of the implements were capable of processing them effectively. If future studies follow the earlier proposed approach, consistently collecting all relevant parameters on the same individual corn stubble, it would be possible to extend the data collection during the node-to-ground distance measurement by recording the position of both the lowest and second-lowest nodes, regardless of their absolute length. This would allow researchers to determine, during subsequent shredding assessments, whether differences exist between treatments in their ability to engage even very short internodes. Such an approach could contribute to a further generalization and refinement of the methodology, enhancing the resolution and robustness of treatment comparisons. In addition, for multi-year studies at different sites, it may be advisable to consider corn stubble moisture content as a further influencing factor.

Brunotte and Vosshenrich (2017) also proposed the assessment of corn stubble condition after harvest and prior to flail mowing as a potential influencing factor. In this method, corn stubble is classified into three categories: (1) firmly standing, (2) bent, and (3) lying flat on the ground. Within the original framework, this classification was intended to help farmers assess whether the number of corn stubble potentially beyond the effective reach of the flail mower's shredding tools was already too high to justify flail mowing from a practical standpoint. In the present study, this rating was also conducted for plots of the two-step method treatment, separately for overrun and non-overrun stubble. However, the results (not shown) only reflected the effect of traffic, i.e., whether the stubble had been run over or not. No further trends within these groups were present. It is conceivable that if all parameters were recorded consistently on the same individual corn stalks, as proposed earlier, this structural rating might yield more differentiated insights. In such a framework, trends in stubble condition could potentially emerge, allowing for a more nuanced interpretation of treatment effects.

Study design constraints on the comparison of tested corn stubble shredding methods

When interpreting the results of the corn stubble shredding intensity assessment, several study design-related aspects need to be considered, as they impose constraints on the comparison of the tested methods. To put the corn stubble shredding performance of the HS3 into perspective, the two-step method treatment was implemented in this study as a benchmark. Since several studies have shown that tractor-driven flail mowers used after harvest represent the most effective method for intensive corn stubble shredding, flail mowers were selected as a best-practice strategy and thus served as the benchmark (Latsch et al. 2010, Uppenkamp et al. 2011, Seidel et al. 2014, Grosa et al. 2016, Uppenkamp 2016, Schneider and Lenz 2017, Uppenkamp and Furth 2020). At the different test sites, various types of flail mowers were used (Table 2). While this approach limits comparability across sites, it captures a broad range of models available on the market, against which the HS3 has to compete.

To enable a comparison as close to practical conditions as possible, the HS3 was equipped with standard knives to simulate the conventional corn header "Horizon Star* II" when harvesting the plots of the two-step method treatment. A cutting height of 15–25 cm was chosen (Table 1), representing a typical stubble height in practice that can be easily achieved with conventional corn headers, which, in contrast to the HS3, are not specifically optimized for operation extremely close to the soil surface. This setting also ensured that the corn stubble could be processed unhindered by flail mowers, i.e., without being bent over by colliding with the mower housing. It should be noted, however, that the choice of cutting height may influence the stubble shredding intensity of the flail mowers used, an aspect that was not investigated in this study.

General comparison of shredding performance under varying site-specific conditions

Already at the beginning of the project, results from the Zeutern and Steinheim sites, and later from the Bückeburg site, showed that the HS3, equipped with newly developed flail knives and used in the single-step method treatment, achieved a shredding intensity comparable to that of conventional flail mowers in the two-step method treatment. Under favorable conditions, both shredding methods were capable of completely destroying more than 84% of the non-overrun corn stubble. Consistent with previous findings, the flail mowers used here were able to reliably engage and shred firmly standing corn stubble (Latsch et al. 2010, Uppenkamp et al. 2011, Grosa et al. 2016, Schneider and Lenz 2017).

However, the results also clearly show that when site-specific conditions are unfavorable, particularly due to low node-to-lowest-working-plane distances, the shredding performance of both treatments is significantly reduced (Figure 8). Even a few centimeters' difference can have a considerable impact. For farmers, this highlights the importance of ensuring a level soil surface during tillage and corn planting.

The data further suggests that the negative effect of a low node-to-lowest-working-plane distance on shredding intensity was more pronounced for the HS3 in the single-step method treatment than for the flail mowers in the two-step method treatment. This was particularly evident at the Timmaspe site, where the average node-to-lowest-working-plane distance was only 4.9 cm, compared to 7.4 cm at the Bückeburg site. Although the total stubble height in the single-step method treatment at the Timmaspe site was only 0.5 cm higher than in the two-step method treatment, the solid segments of the corn stubble averaged 6.6 cm compared to just 3.4 cm in the two-step method treatment, indicating much less fragmentation, as reflected in the rating results with 37% and 76% completely destroyed corn stubble in the single-step and two-step method treatments, respectively.

This is likely attributable to two main factors. First, tractor-driven flail mowers can generally be operated at a lower cutting height, since occasional soil contact poses less of a risk. In contrast, the HS3 corn header must avoid ground contact to prevent engine speed drop and overloading of the combine harvester's drive system (Ramm et al. 2023). Second, the tool design plays a crucial role. The hammer flails used in the flail mower have a high momentum and can perform a low, horizontal cut close to the soil surface. In contrast, the angled design of the HS3's flail knives limits how close they can operate to the ground, likely contributing to the higher proportion of undisturbed solid stubble segments under unfavorable conditions (Figure 1).

Initially, the poor shredding performance of the HS3 at the Timmaspe site was attributed to the absence of an automatic row guidance system on the combine harvester, which may have caused the row-dependent flail knives of the HS3 to engage the stubble at suboptimal angles. However, the insights gained from the newly introduced parameter node-to-lowest-working-plane distance strongly suggest that the unfavorable conditions at this site—rather than issues of tool alignment—were the primary reason for the reduced shredding intensity.

At the Kraichtal site, particularly large variations were observed in the assessment results for corn stubble shredding intensity within the single-step method treatment. Although the soil surface was very even, the node-to-lowest-working-plane distance averaged only 5.7 cm due to a comparatively low node-to-ground distance. Additionally, some plots exhibited considerable lateral slope, most notably in Block A with an average inclination of 8.2°. In this plot, the HS3 equipped with flail knives was unable to completely destroy any corn stubble. These findings support the hypothesis that lateral slope may negatively affect the working quality of the row-guided HS3 header.

Shredding tool positioning and corn header design approaches

The findings presented above underline the importance of correct positioning of the shredding tools relative to the corn stubble in order to achieve the desired shredding effect. For the HS3, this positioning depends on the precision of the header's height guidance system, which is linked to the electrohydraulic controls of the combine harvester. The signals from the HS3 are processed by this system to adjust the feederhouse position and tilt angle, so that the responsiveness and accuracy of the combine harvester directly influence the shredding quality of the HS3.

Another approach has been introduced by Claas Selbstfahrende Erntemaschinen GmbH (Harsewinkel, Germany) with the "Corio Stubble Cracker" system. In contrast to the integrated tool concept of the HS3, this system consists of separate shredding units mounted on swinging arms at the rear of the corn header. Each unit combines two rotating skids, with each skid following one row of corn stubble. The vertical movement of the units and their ability to compensate for tilt allows each unit to follow the ground contour independently of the corn header (Herter and Schwaer 2022). While this design may help to improve contour following, it also increases the mechanical complexity of the corn header.

However, based on the currently available data, a direct comparison between the "Corio Stubble Cracker" system and the HS3 is not possible. This applies in particular in light of the present findings, which clearly demonstrate how strongly varying field conditions influence shredding performance. Further trials would therefore be required to assess the potential of such systems under comparable site conditions.

Effect of overrun corn stubble on shredding performance

The main advantage of combining corn harvesting and corn stubble shredding into a single pass became particularly evident in the combine harvester's track zones, i.e., in the case of overrun corn stubble. As demonstrated in previous studies, flail mowers often encounter significant difficulty in effectively engaging and shredding stubble that has been flattened by the combine harvester's tracks and tires (Uppenkamp et al. 2011, Klingenhagen et al. 2014, Grosa et al. 2016, Brunotte and Vosshenrich 2017, Schneider and Lenz 2017). This issue was clearly reflected in the results of the two-step method treatment. At the Bückeburg site, the proportion of completely destroyed overrun corn stubble was 72 percentage points lower compared to non-overrun stubble. At the Kraichtal site, the difference was 43.3%. At locations where the overall shredding intensity was already reduced due to unfavorable conditions, the effect of overrunning was correspondingly smaller. For example, the differences between overrun and non-overrun stubble were 40.0%, 33.7%, and 3.4% at the Timmaspe, Stettfeld, and Steinheim sites, respectively.

In contrast, the results for the HS3 in the single-step method treatment revealed a distinctly different pattern. At every site, the proportion of completely destroyed corn stubble was consistently higher in the combine harvester's track zones compared to non-overrun areas. Increases of around 6–7% were observed at the Steinheim and Bückeburg sites. At the Kraichtal and Wöbs sites, the differences were more pronounced, reaching 23% and 21%, respectively. The greatest increase was recorded at the Timmaspe site, where overrun corn stubble showed a 30% higher destruction rate than non-overrun stubble. This effect can be attributed to the sequence of operations in the single-step method: the stubble is first cut short by the HS3's flail knives before being run over by the combine harvester‘s tracks and tires. The reduced leverage of the shortened stubble prevents it from bending or folding. Instead, the stubble tends to split open when driven over, thereby enhancing the overall shredding intensity.

As outlined in the Introduction and based on findings by Augustin et al. (2020), it can be assumed that during grain corn harvest with an 8-row corn header and 75 cm row spacing, at least 35% of the corn stubble is driven over by the tracks and tires of the combine harvester. When the results from the assessment of corn stubble shredding intensity are weighted accordingly, i.e., assuming 65% non-overrun and 35% overrun corn stubble, the advantage of track-independent shredding becomes even more apparent. At the Bückeburg site, the flail mower in the two-step method treatment would have achieved only 59% completely destroyed corn stubble when weighted, despite processing over 84% of the non-overrun stubble effectively. In contrast, the HS3 in the single-step method treatment would have achieved 91% completely destroyed corn stubble, thanks to its superior performance in the overrun zones. At the Timmaspe site, the flail mower would have reached 63% destruction on a field-average basis, while the HS3 would have achieved 47.5%, despite destroying only 37% of the non-overrun corn stubble. This outcome highlights the compensating effect of improved shredding intensity in the overrun zones for the HS3. At the Wöbs site, the effect is also noteworthy: 73% destruction in non-overrun areas and 94% in overrun zones translate into a field-average shredding intensity of 80% completely destroyed corn stubble when weighted. These figures clearly demonstrate the significant impact that combine harvester traffic lanes have on overall shredding performance.

Conclusions

This study demonstrates the potential of combining grain corn harvest and stubble shredding into a single operation to optimize both processing effectiveness and operational efficiency, while also identifying opportunities to improve the experimental approach. The key recommendations are as follows:

- Further methodological improvements: As outlined in the discussion, several refinements are recommended to improve data consistency and enable a deeper understanding of influencing factors on shredding intensity. Future studies should consider the following approach:
  - Measurement of soil surface conditions across the full working width of the corn stubble shredding implement, conducted prior to harvest in the standing crop.
  - Simultaneous measurement of node-to-ground distances on the same corn plants.
  - Marking of the stalk base and surrounding area of the examined plants to allow for post-harvest reassessment.
  - After stubble treatment, assessment of shredding intensity, total stubble height, and height of the solid stubble segment, recorded at the previously marked corn stubble, differentiated for overrun and non-overrun corn stubble.
  - Measurement of the rut depth caused by the combine harvester's tracks and tires.

  This procedure would allow for consistent, plant-specific datasets rather than plot averages, enabling more detailed statistical analyses and a more precise evaluation of interaction effects. The practical feasibility of this approach should be tested in future field trials.
- Benchmark comparison and agronomic implications:
  - The HS3, equipped with newly developed flail knives, achieved shredding intensities for non-overrun corn stubble comparable to those of conventional, tractor-driven flail mowers used post-harvest, provided that site-specific conditions were favorable.
  - The key advantage of the HS3 lies in its independence from the adverse effects of combine harvester tracks and tires. While conventional flail mowers showed a significant decline in performance on overrun stubble, the HS3's single-pass system—cutting the stubble short before it is run over—increased shredding intensity in these areas. As a result, overall field-wide processing quality can be significantly improved.
  - The HS3 enables the elimination of an additional field pass for stubble shredding. This study demonstrates that, where a level soil surface has been established through precise tillage and sowing, the single-step method can offer both agronomic and operational advantages over conventional two-step systems.
  - The combination of node-to-ground distance and soil surface condition into the composite parameter node-to-lowest-working-plane distance proved to be a key determinant of shredding success. The data suggest that shredding performance with the HS3 was more negatively affected by low node distances above the working plane than with post-harvest flail mowers used in the two-step method.
  - The results indicate that the performance of the row-guided HS3 may be compromised in areas with considerable side slope inclination. This warrants further investigation in future field trials. In contrast, conventional flail mowers are unaffected by slope due to their full-width design.

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