Can precision seeding improve winter wheat establishment?

A comparative field study between precision seeding and conventional seeding of winter wheat at three different seeding rates

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Abstract

Despite historical increases in winter wheat yields is the current trend showing signs of yield stagnation. This stagnation is a cause for concern when considering the escalating food demand due to a growing global population. Nonetheless, it is still evident that there remains a greater genetic potential for further increases in winter wheat yields and precision seeding of winter wheat stands out as one possibility to elevate productivity, both through an improved seed singulation and reduced seed depth variability. Therefore, this study aimed to investigate whether a precision seeder adapted for small grains could improve the establishment of a winter wheat crop. In contrast to earlier studies, the emphasis was not only on investigating seed placement, but also on analyzing how seed placement affects emergence and plant development. A field experiment was thus carried out in southern Sweden to compare a precision seeder prototype to a conventional seed drill at three different seeding rates, 188, 281, and 375 seeds/m^2. Crop establishment was assessed by investigating seeding depth, seed singulation, emergence, and plant development. The results show that precision seeding has the potential to improve winter wheat establishment, both through improved seed singulation and reduced seed depth variability. However, the improved seed singulation does not appear to be that advantageous at higher seeding rates or wider row spacings, as this results in plants being positioned closer together within the seed row. Furthermore, to fully unlock the potential of a reduced seed depth variability, all seeds must germinate promptly upon seeding to achieve a uniform emergence and plant development. During this field trial, both seeders were configured with different row spacings and fertilizer placements, which implies that further research is required to better understand the sole impact of an improved seed singulation and reduced seed depth variability on emergence and plant development, but also their subsequent contributions to the final yield.

Keywords: Precision seeding, Winter wheat, Emergence, Plant development, Seeding depth, Seed singulation

Sammanfattning

Trots historiska ökningar av höstveteskördarna visar den nuvarande trenden tecken på att skördeutvecklingen avtar. Denna stagnation är oroande med tanke på den ökande efterfrågan på livsmedel till följd av en växande global befolkning. Trots detta är det fortfarande tydligt att det finns en större genetisk potential för ytterligare skördeökningar och precisionsådd av höstvete framstår som en möjlighet till att öka produktiviteten, både genom en förbättrad frösingulering och minskad sådjupsvariation. Syftet med studie var därför att utvärdera om en precisionssåmaskin, specifik designad för spannmål, kunde förbättra etableringen av höstvete. Till skillnad från tidigare forskning, inriktades inte studien enbart på utsädesplaceringen, utan också på hur utsädesplaceringen påverkade uppkomsten och plantutvecklingen. Ett fältexperiment genomfördes därför i södra Sverige för att jämföra en precisionssåmaskinsprototyp mot en konventionell såmaskin vid tre olika utsädesmängder, 188, 281 och 375 frön/m^2. Grödetableringen utvärderades genom att analysera sådjup, frösingulering, uppkomst och plantutveckling. Resultaten tyder på att precisionssådd kan bidra till att förbättra etableringen av höstvete, både genom en förbättrad frösingulering och minskad sådjupsvariation. Den förbättrade frösinguleringen antas dock inte bli lika fördelaktig vid högre utsädesmängder eller bredare radavstånd, eftersom detta resulterar i att plantorna placeras närmare varandra i såraden. Dessutom, för att helt utnyttja potentialen med en minskad sådjupsvariation måste samtliga frön gro direkt vid sådd för att uppnå en jämn uppkomst och plantutveckling. Under detta fältförsök var båda såmaskinerna konfigurerade med olika radavstånd och gödselplaceringar, vilket antyder på att mer forskning behövs för att få en bättre förståelse över den enskilda effekten av en förbättrad frösingulering och minskad sådjupsvariation på uppkomsten och plantutvecklingen, men också deras efterföljande bidrag till den slutliga skörden.

Nyckelord: Precisionssådd, Höstvete, Uppkomst, Plantutveckling, Sådjup, Frösingulering

Table of contents

List of tables

List of figures

1. Introduction

Wheat, harvested somewhere on the globe every month of the year (AMIS 2022), has with better farming practices and innovations experienced an increase in productivity, ensuring a more abundant and reliable source of this essential staple food. Despite historical increases in winter wheat yields is the current trend showing signs of yield stagnation, particularly in Europe (Olesen et al. 2010; Ray et al. 2012, 2013; Schauberger et al. 2018). This stagnation is a cause for concern when considering the escalating food demand due to a growing global population (Hunter et al. 2017). However, there is still proven to be a higher genetic potential for further improvements in winter wheat yields (Senapati & Semenov 2020), and several projects are currently attempting to close this yield gap (ADAS 2023; Great Lakes YEN 2023). To achieve higher wheat yields with increasing expectations related to sustainability and efficiency, new management practices have to be tested.

During the ongoing efforts to increase winter wheat yields, precision seeding stands out as one possibility to elevate productivity, and multiple machinery manufacturers have initiated exploration into this area (Horsch 2023; Väderstad 2023). But as of now, there is no precision seeder adapted for small grains currently available on the market. However, this is most likely to be changed in the near future (ATL 2023). Precision seeding technology is well known from crops like maize and soybeans and involves a precise and equal spacing of seeds within the seed furrow, also known as seed singulation (Murray et al. 2006). This improved seed singulation, along with a reduced seed depth variability, has the potential to improve both establishment and final yield in these precision seeding crops. (Krall et al. 1977; Carter et al. 1989; Nielsen 1993; Anderson 2022; Kimmelshue et al. 2022). Traditionally, winter wheat and other small grains have been sown using a seed drill, which follows a random distribution of seeds within the seed furrow (Murray et al. 2006). However, the adaptation of precision seeding has in recent studies shown to increase winter wheat yields between 5% and 11%, using custom-designed seeders or planters used for row crops, seeking to replicate the potential results achieved with a small-grain adapted precision seeder (Bund 2021; Copeland et al. 2021). Precision seeding of winter wheat also comes with the possibility of lowering seeding rates without compromising yield and economic return (Bund

2021). A more uniform seeding pattern also reduces the intra-specific plant competition, allowing for an increased water use efficiency (16.7% to 32.9%), and nitrogen use efficiency (3.8% to 10.9%) (Tao et al. 2019). Precision seeding thus entails reducing inputs while still maintaining or increasing yields. However, there is yet no indications of how precision seeding is affecting winter wheat emergence, emergence uniformity and variability in crop phenological development. To get a better understanding of how this increased yield potential is created, it becomes essential to overlook how a more precise seed placement is affecting the establishment, which plays a vital role in maximizing the yield potential of a winter wheat crop.

Given this information, a field trial experiment was conducted to see how precision seeding could improve the establishment of a winter wheat crop. The experiment involved a comparison between a precision seeder prototype adapted for small grains and a conventional seed drill to address the following hypothesis:

1. Seed depth variability will be reduced with the use of a precision seeder compared to a conventional seed drill
2. The seed singulation quality will improve with the use of a precision seeder compared to a conventional seed drill
3. Precision seeding will ensure a faster and more uniform crop emergence compared to conventional seeding
4. Precision seeding will ensure a faster and more uniform crop development compared to conventional seeding.

2. Background

2.1 Winter wheat establishment

The first step towards a productive winter wheat crop is to ensure a successful establishment. This process begins when the farmer places the seed in the soil. The seed then requires water, oxygen, and favourable temperatures to germinate (Anderson & Garlinge 2000; John et al. 2011). It is crucial to facilitate proper seed-to-soil contact to maintain a sufficient level of moisture during this phase. Seeds lacking sufficient soil contact will have reduced protection against evaporation and becomes more vulnerable to wetting and drying cycles, causing an inefficient water transfer from the soil to the seed (Håkansson et al. 2008; John et al. 2011). Following a successful germination, leading up to emergence, plant development is primarily governed by temperature and seeding depth (Karow et al. 1993). The ideal seeding depth for winter wheat is achieved when seeds are uniformly placed at 2.5 cm, but seeds should always be placed into moisture to ensure a uniform emergence, even if this means seeding deeper (Bagg et al. 2017). However, placing seeds deeper than 10 cm should be avoided as emergence and plant vigor can be badly affected, leading to a reduced yield potential (Hadjichristodoulou et al. 1977; Gan et al. 1992). On the other hand, seeding shallower than 2.5 cm increases the risk of not seeding into moisture, causing a poorer and delayed emergence (Håkansson et al. 2008; Hooks n.d.). A seeding depth shallower than 2.5 cm also increases plant vulnerability to frost and frost heaving's, as it exposes the growth point and positions the crown roots closer to the soil surface (Eriksson & Magnusson 2014; Bagg et al. 2017). To ensure that all seeds are placed into moisture, seeds should be placed at a depth between 3 and 4 cm when using a seed drill, due to the variability in seed depth placement (Bagg et al. 2017). A precision seeder can on the other hand significantly reduce seed depth variability (Canfield et al. 2019). This is possible due to the gauge wheel alongside the disc opener, which positively regulates the disc and ensures that all seeds are placed in the soil at a consistent depth (Bagg et al. 2017). If seed depth variability decreases, the risk of placing seeds into dry soil declines, allowing for placement of seeds closer to the ideal seed depth of 2.5 cm. A reduced seed depth variability also facilitates a higher probability of a more uniform emergence, as all seeds will have the same temperature requirement before emerging (Karow et al. 1993). If plants do not emerge uniformly, the early-emerging plants will diminish the yield potential of the smaller later-emerging plants, as demonstrated by Gan et al. (1992). Their research revealed that plants emerging within the first three days will produce 1.4 times the grain yield of the plants emerging on day 4 to 6, and 3.2 times more than those emerging on day 7 to 9. This same phenomenon is also well documented in grain maize where research also shows that the early-emerging plants cannot compensate for the yield loss of the smaller later-emerging pants, leading to an overall yield loss (Carter et al. 1989). However, how the relative date of winter wheat emergence will affect the overall yield has not been extensively studied. But achieving a more uniform emergence will ultimately leave a crop stand with more equally sized plants (Gan et al. 1992). A crop stand with less variability in crop phenological development could present opportunities for more informed management decisions, like the use of plant growth regulators, fungicides and herbicides, as these are ideally applied during a specific development stage. Fast emergence is also an important component during establishment, as this enables for early growth, ultimately leading to a competitive crop during the early stages, something that is especially important against weeds (Fahad et al. 2015).

The presence of phosphorus plays a vital role in the success of a winter wheat crop, which can be applied through a starter fertilizer in the autumn. Phosphorus helps to promote plant growth (Crozier et al. 2013; Bagg et al. 2017) and improves frost tolerance (Crozier et al. 2013). It also allows plants to mature earlier and more evenly. As seeding is postponed, the value of a starter phosphorus fertilizer becomes even more critical to ensure high winter survival and grain yield (Knapp & Knapp 1978). The application of autumn nitrogen applications can also be an option. However, nitrogen should not be applied in larger quantities, as winter wheat usually does not take up more than 20 kg of nitrogen per hectare during the autumn (Lindén 2000). Nitrogen can, despite lower quantities, help promote the development of autumn tillers (Alley et al. 2009). The ideal situation is to develop one to two autumn tillers for a winter wheat plant, (Eriksson & Magnusson 2014), meaning that the ideal crop stage before winter is between 21-22 when using Zadoks development scale (Zadoks et al. 1974). Autumn tillers are vital to ensure high yields of winter wheat (Thiry et al. 2002). Plants with inadequate autumn tillers cannot fully compensate for this by producing spring tillers, as these have a lower harvest index and produce a lower grain yield (Thiry et al. 2002). However, an excessive number of tillers can cause high competition among neighbouring plants, causing a lower tiller survival and a lower harvest index. Another risk associated with an overdeveloped plant is the potential rise and exposure of the growth point, leading to an increased vulnerability to frost (Eriksson & Magnusson 2014). Conversely, a small and underdeveloped plant will have a smaller root system which possesses fewer nutrient resources, posing challenges related to frost heaving's and dehydration damages. An underdeveloped root system also limits the potential for water and nutrient uptake, which can be markedly important during a dry spring (Hoad et al. 2004), something that regularly can occur in the eastern parts of Sweden (Eriksson & Magnusson 2014).

2.2 Winter wheat development

One common way to monitor winter wheat development is by using temperature accumulations over time, which can be monitored using growing degree-days (GDD). McMaster & Wilhelm (1997) discuss two comparable interpretations for calculating GDD. The main difference between the two methods is how the temperature is integrated with the base temperature. In this study, the following method will be used: $GDD=[(T_{MAX}+T_{MIN})/2]-T_{BASE}$, where the average day temperature is subtracted by the base temperature (T_{BASE}). The base temperature is the threshold below which a specific process of interest does not advance. However, this can vary depending on the development stage and winter wheat variety (Slafer & Rawson 1995). To simplify, 0°C is commonly implemented as the base temperature for winter wheat (Kirby et al. 1985; Baker et al. 1986; Karow et al. 1993; Fowler 2018).

During the establishment phase of a winter wheat crop, development consists of three primal stages. These stages are germination and emergence, seedling growth, and tillering (Zadoks et al. 1974). The germination process starts when the seed absorbs water, followed by the emergence of the radicle and coleoptile (Zadoks et al. 1974). The first seminal roots are then developed, and the coleoptile starts to elongate, which protects the first leaf during emergence (Karow et al. 1993). The initial leaf will then emerge through the tip of the coleoptile. However, when seeds are sown too deep, there is a higher risk of the first leaf emerging beneath the soil surface. In such cases, the leaf lacks the stiffness to penetrate the soil like the coleoptile and may become defective (Hines et al. 1991; Karow et al. 1993; Kirby 1993). The duration for completing germination and emergence depends on the interaction between soil temperature, soil-water content, and seeding depth (Lindstrom et al. 1976; DeJong & Best 1979). If the seed is placed in moist soil, then the germination process requires approximately 80 GDD, while the duration from coleoptile elongation to final emergence requires 20 GDD per centimeter of seed depth (Karow et al. 1993). The seedling stage initiates with the appearance of the first leaf, during which additional seminal roots develop, and the crown becomes noticeable (Fowler 2018). The leaves will then emerge in a defined pattern, which is called a phyllochron (Anderson & Garlinge 2000). In general, most winter wheat varieties have a phyllochron of 100 GDD, which means that the time between the appearance of two successive leaves requires a temperature accumulation of 100 GDD (Karow et al. 1993; Anderson & Garlinge 2000; Fowler 2018). However, this interval can fluctuate based on variety and environmental conditions (Johansson 1955; Anderson & Garlinge 2000; Fageria et al. 2006), leading to a phyllochron interval ranging between 75 and 120 GDD (Karow et al. 1993; Oakes et al. 2016; Fowler 2018). The tillering stage begins when the plant has developed three leaves on the main stem and the first tiller starts to emerge (Fowler 2018). Tiller one will develop from the first leave on the main steam, and the second tiller will develop from the second leave, and so on (Karow et al. 1993). Leave and tiller production is synchronized so that the first tiller will appear at the same time as the fourth leave and the second tiller at the same time as the fifth leave. Later on will secondary tillers develop from these primary tillers in the same synchronized pattern.

Recognizing the various development stages of a winter wheat crop is essential for farmers, as it guides them in making informed management decisions. Applying fertilizers and pesticides at the right development stage ensures extracting the maximum value from the product. Today there are several scales used by producers to determine the development stages of a winter wheat crop. Some of these are the Feeks, Zadoks, and BBCH scales (Large 1954; Zadoks et al. 1974; Meier 2001). The Feeks scale is more common in the United States, while the Zadoks and BBCH scales are more frequently used in Europe (Wise et al. 2011).

2.3 Precision seeding of winter wheat

Precision seeding helps improve the spatial distribution of winter wheat plants within the seed row (Canfield et al. 2019; Bund 2021). This improved spatial distribution is achievable through the vacuum disc precision meter system, allowing for a precise and equal spacing of wheat seeds within the seed furrow, also known as seed singulation (Murray et al. 2006). Seed singulation is quantified using a statistical metric known as the coefficient of variation (CoV) (Bund 2021). When seeding winter wheat, a conventional seed drill typically exhibits a CoV of approximately 100%, whereas a precision seeder tends to show a slightly lower value (Canfield et al. 2019; Bund 2021). In this case, a lower CoV is better and gives indication of an improved seed singulation. The adaptation of precision seeding has in recent studies shown to increase winter wheat yields between 5% and 11%, by using custom-designed seeders or planters used for row crops, seeking to replicate the potential results achieved with a small-grain adapted precision seeder (Bund 2021; Copeland et al. 2021). Precision seeding of winter wheat also has the potential to reduce seeding rates without compromising yield and economic return (Bund 2021). A more uniform seeding pattern also reduces the intra-specific plant competition, allowing for an increased water use efficiency (16.7% to 32.9%), and nitrogen use efficiency (3.8% to 10.9%) (Tao et al. 2019). However, the increased yield potential seems limited at higher seed densities, given the decreased distance between plants within the seed row (Bund 2021).

Precision seeding is commonly used in row crops like maize, which is planted with seeding rates from 5 to 10 seeds/m^2, at row spacings between 50 and 90 cm (Bagg et al. 2017). Winter wheat is typically sown using a seed drill equipped with mass flow metering, metering the correct seed quantity for a specific area (Murray et al. 2006). Seeding rates are significantly higher in winter wheat (350-450 seeds/m^2), and row spacings are much narrower (10-25 cm) compared to maize (Bagg et al. 2017). Precision seeders have historically been designed to singulate seeds in row crops like maize, which makes it harder to realize a singulation metering system in winter wheat, given the higher seeding rates. Singulation of individual wheat seeds could, however, be more feasible at lower driving speeds or narrower row spacing, which, on the other hand, requires more working hours or larger machine widths, and narrower row spacing is likely to pose technical challenges (Bund 2021). The most effective approach is probably to reduce seeding rates, as winter wheat can produce more grain-bearing tillers per plant at lower seed densities (Gooding et al. 2002). This could also be combined with hybrid wheat varieties, exhibiting increased tillering capacity, attributed to the heterosis effect (Rai et al. 1970), providing room to reduce seeding rates even more. Nevertheless, lower seeding rates require a growing season of adequate length to facilitate more tillers per plant, and to sustain yields at reduced seed densities, it becomes even more critical to create good seedbed conditions to guarantee a successful establishment (Bund 2021). However, there is still little knowledge on how precision seeding of winter wheat affects establishment, which plays a vital role in maximizing the yield potential of a winter wheat crop. If precision seeding could facilitate quicker emergence and plant development, it might create opportunities for postponing the seeding date while still ensuring robust plant growth. Something that could alleviate issues related to pests and pathogens (Eriksson & Magnusson 2014). Delaying the seeding date also diminishes the weed pressure (Ona et al. 2018), and with an accelerated plant development during the autumn, the potential decrease in yield might not be as significant. Moreover, less variability in crop phenological development might enhance the effectiveness of various management practices, such as fungicide applications or the use of plant growth regulators, as these are ideally applied during specific developmental stages.

3. Method

3.1 Site description and soil characteristics

A field experiment was carried out during the autumn of 2023, outside the town of Mjölby, in south of Sweden (58°19'17.1"N, 14°57'50.9"E), a region that is characterized by a humid continental climate (Beck et al. 2018). The area has an average annual temperature of 7°C and a yearly precipitation averaging 582 mm (SMHI 2023a). The topsoil at the experimental site had an average clay content of 18% with a soil organic matter content of 3.1% (Table 1). Soil pH was measured to 6.2 using the H_2O-method (Jordbruksverket 2024), and nutrient values were relatively abundant (Eurofins 2023).

Table 1. *Soil characteristics from the experimental site*

Clay content (%)	Soil organic matter (%)	pH	P-AL (mg/100g)	K-AL (mg/100g)	Mg-AL (mg/100g)
18	3.1	6.2	7.2	11.2	9.6

3.2 Experimental design and treatments

The experimental setup followed a randomized complete block design (Figure 1). The design included six treatments and three replicates (blocks). Each treatment corresponded to a given combination of seeding method, either precision seeding or conventional seeding, and seeding rate, 375 seeds/m^2 (100%), 281 seeds/m^2 (75%), or 188 seeds/m^2 (50%). The seed drill operated with a width of four meters, while the precision seeder had a working width of six meters. Each block had a length of approximately 150 meters.

Block 1						Block 2						Block 3					N⇧
75%	75%	100%	100%	50%	50%	100%	50%	75%	50%	100%	75%	100%	100%	75%	50%	75%	50%
PS	Drill	Drill	PS	PS	Drill	PS	Drill	PS	PS	Drill	Drill	PS	Drill	Drill	Drill	PS	PS

Figure 1. *Experimental design overview, with the precision seeder (PS) and seed drill (Drill) at three seeding rates, 50, 75 and 100%. The northward direction is displayed in the top right corner to indicate the orientation of the field experiment.*

3.3 Seeding concepts

3.3.1 Precision seeder

The precision seeder featured a central fill tank for seeds and a front-mounted fertilizer hopper, along with two ranks of row units, put together at a row spacing of 22.5 cm (Table 2). Each row unit had a reconsolidation wheel in front to create even seeding conditions for all row units and was shortly followed by a row cleaner for residue management. The row units had a double disc coulter, with two gauge wheels positioned beside each disc, which positively regulated each disc to ensure that all seeds were placed in the soil at a consistent depth. The vacuum disc precision meter system allowed for an equal spacing of seeds in the seed furrow, also known as seed singulation. The starter fertilizer was seed-placed along with the seed. Lastly, two closing wheels pushed the open seed slot all together.

3.3.2 Conventional seed drill

The conventional seed drill had a modern design and featured a hopper capable of holding both seeds and fertilizer in two separate compartments, along with two ranks of seed coulters, with a row spacing of 12.5 cm (Table 2). The starter fertilizer was side-banded between every other seed row at a spacing of 25 cm, using a third row of coulters in front of the seed coulters. The seed coulters were of a single disc coulter type, followed by a large packer wheel and then a following harrow. The seed drill was additionally equipped with a front tool comprised of two rows of discs for seedbed preparation.

3.4 Seeding and crop management

Seeding took place on September 15th and 16th, falling within the recommended seeding window for the region, which spans from September 10th to September 20th (Eriksson & Magnusson 2014). Due to a smaller unexpected malfunction on the precision seeder, the seed drill treatments underwent a delay and were sown on the following day, which explains the difference in seeding dates (Table 2). Prior to seeding, the field underwent two passes with a combination cultivator, and the preceding crop was oilseed rape. The selected winter wheat variety was RGT Koi, with a thousand-grain weight of 43 and a germination rate of 98%. The seed rate was set to 375 seeds/m^2, which is common in the region at this time of year (Lantmännen 2023), along with 281 seeds/m^2 and 188 seeds/m^2. The seeding depth turned out to be approximately 2.4 cm for the precision seeder and 4.4 cm for the seed drill, and the intention was not for the precision seeder treatments to be sown 2 cm shallower. At seeding, 125 kg of starter fertilizer (NPK 8-10.5-14) was applied. The fertilizer was seed-placed with the precision seeder and side-banded with the seed drill at a spacing of 25 cm (Table 2). The field had a notable weed biomass and was sprayed with a prosulfocarb product (Boxer) on October 18th. Following the application, the herbicide effectively controlled the weed pressure.

Table 2. *Field trial details and seeder configurations for precision seeder (PS) and seed drill (Drill).*

Seeder	Seed rate (seeds/m^2)	Seeding date	Fertilizer placement	Row spacing (cm)
PS	375	Sep 15th	Seed-placed	22.5
PS	281	Sep 15th	Seed-placed	22.5
PS	188	Sep 15th	Seed-placed	22.5
Drill	375	Sep 16th	Side-banded	12.5
Drill	281	Sep 16th	Side-banded	12.5
Drill	188	Sep 16th	Side-banded	12.5

3.5 Meteorological overview

The autumn of 2023 presented exceptional challenges due to significantly higher precipitation levels in the region. In August, the total precipitation reached 171 mm, a substantial change from the usual 72 mm (Figure 2) (SMHI 2023a; b). Despite temperatures in August being close to the monthly average, the persistent rain posed difficulties during harvest and tillage operations. In September, precipitation levels returned to near-average, providing a broader seeding window between September 2nd and September 17th. From September 18th to September 20th, a 6 mm rainfall occurred, resulting in the field trial being exposed to rain shortly after sowing. September temperatures were otherwise notably higher than the average. Both October and November also received more rain than normal. Over all four months, there had been a total rainfall of 387 mm. Additionally, October and November were colder than the average, with temperatures dropping below 0°C on November 14th. The total temperature accumulation was otherwise near average at the end of November.

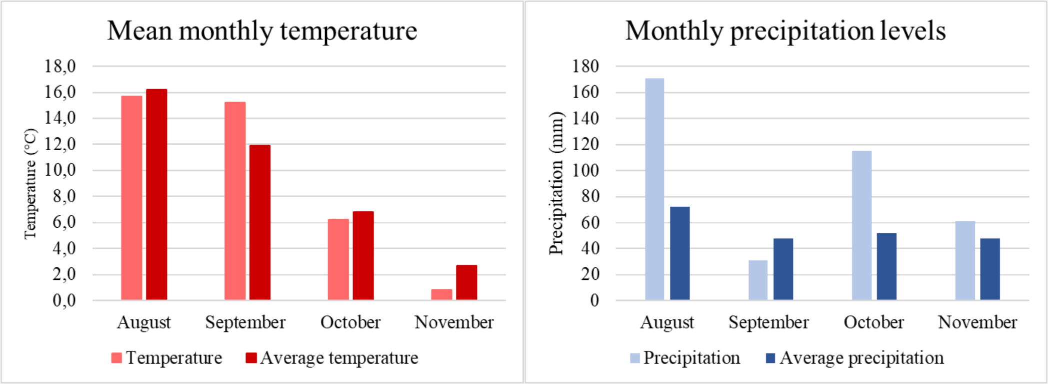

Figure 2. *Mean monthly temperature (°C) and monthly precipitation (mm) between August 1st and November 30th at Härsnäs, near the field trial, along with average precipitation levels and temperatures for the same location.*

3.6 Measurements and evaluation

Data gathering occurred between September and December and eighteen grading sites were selected in the field. The locations were intentionally selected in the field to get similar field conditions for both seeders, ultimately to provide a better comparison. Each grading site, with an area of 0.5 m^2, was placed 30 meters into the experimental trial from the field's southern edge. Since the grading sites were intended to be uniform, there was a variation in placement of plus-minus two meters. The grading area of 0.5 m^2 was then split up into two seeding rows. Two seeding rows were considered better than one in case something happened to the first row during seeding, and having more than two rows was not considered ideal either, as it would result in very short row lengths. Both seeding rows meant for measurements were subsequently placed in the center section of both seeders to prevent the results from being influenced by tractor wheel tracks or variations between the outer sections of the seeders. The chosen seed rows for each seeder are displayed in Figure 3 as four rings with solid lines. Initially, the plan was to position both seeding rows 56.25 cm from the center in each direction, as both seeders would have had seed coulters at these positions within the center section. Regrettably, there were some minor hiccups. The precision seeder's rear rows pushed soil onto the front rows that were already sown, thereby impacting the seeding depth. This soil ridge on every other row is marked with an A in Figure 3. The rear rows on the other hand, had a tendency towards a more open seed slot, marked with B in Figure 3. It was considered better to do measurements in the seed rows without ridges (B) since these were closer to a representative result. One row on the precision seeder also emerged much earlier than the rest and was subsequently left out in the evaluations, marked with B* in Figure 3. Consequently, measurements in the initial seed row on the precision seeder, marked with a dashed circle in Figure 3, had to be shifted three rows to the right. The seed row on the left-hand side of the seed drill was chosen to remain in its current position since there was a tendency towards an elevation in the center of some seed drill treatments, marked with C in Figure 3.

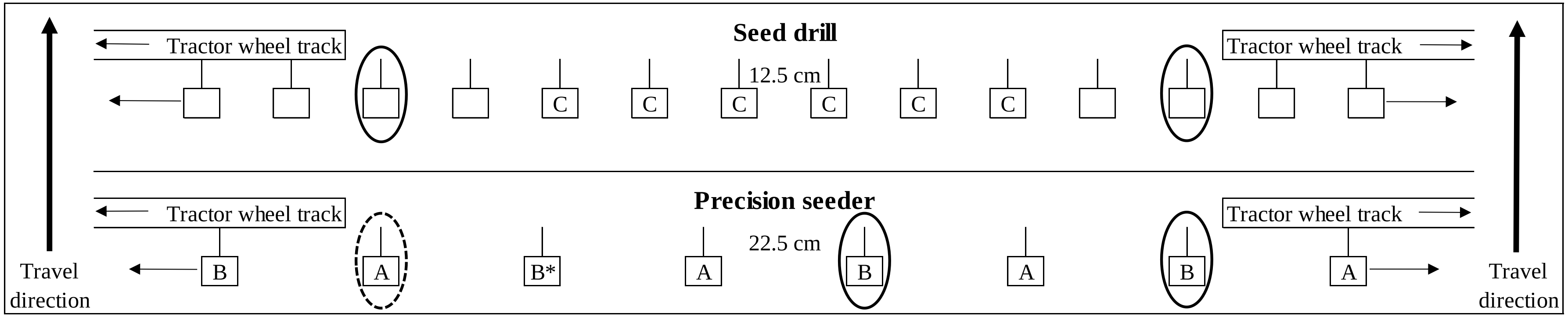

Figure 3. *Each square represents a seed row (seed coulter) in the middle section of the seeder, precision seeder (bottom, with 22.5 cm row spacing) seed drill (top, with 12.5 cm row spacing). Chosen seed rows for measurements are marked with circles (solid lines). The dashed circle marks the primary selected seed row for the precision seeder but was swapped out because every other seed row had a soil ridge (marked with A). Seed rows marked with B had a tendency towards an open seed slot but were considered to be fine for measurements. One row on the precision seeder had an odd emergence and was left out in the selection for this reason (marked with B*). The seed drill created an elevation among the six middle seed rows in some treatments, which ruled out these rows in the selection (marked with C). Tractor wheel tracks and direction of travel are displayed on the left- and right-hand side.*

3.6.1 Crop emergence

Crop emergence was defined as the point at which the wheat plant had grown to a height of five centimeters above the soil surface. A height of five centimeters was deemed to be a reasonably optimal threshold. A plant in the range below five centimeters may have been more susceptible to disturbances caused by field irregularities or when encountering stones or other obstacles. A plant that just emerged through the soil is also more challenging to detect, and the risk of leaving a few out could have been higher. When the height instead exceeds five centimeters, differences in height would have become more challenging to determine. Moreover, variations in plant vigor may arise at this stage due to factors like nutrient availability, which also could contribute to differences in plant height. Crop emergence assessment took place over an entire week, from September 25th to October 2nd and a final count was done on October 11th to catch any descendants. The assessment was conducted on both seeders across all three seeding rates. The evaluation was performed in two seed rows for each seeder (Figure 3). Due to the varying row spacing between the seeders, the lengths of the two rows were adjusted to be consistent at 0.5 m^2. Thus, the seed rows became 111 cm in length in the precision seeding treatments, whereas the seed rows in the seed drill treatments were extended to 200 cm. Each day, a count was completed for all emerged plants in the two chosen rows, resulting in a progressively higher number each day.

Temperature accumulations over time are often used to evaluate the progress of emergence. In this study, growing degree-days (GDD) will be used to monitor the accumulated temperature (Eq. 1). GDD is determined by subtracting the base temperature from the daily mean temperature:

$$GDD = [(T_{MAX}+T_{MIN})/2]-T_{BASE} \qquad \text{(Eq. 1)}$$

As winter wheat has a base temperature of 0°C, the calculation becomes easy and involves simply adding up the daily mean temperatures. GDD is more accurate than just using days from seeding to emergence, as the rate of emergence is influenced by temperature. This approach also enables a meaningful comparison of the two seeders despite differences in sowing dates.

To compare the time of emergence between both seeders, emergence was split up at three points in time: initial emergence (when the first seedling reached a height of five cm), 50 and 90% emergence. These events were determined by examining the emergence graphs for each replicate. While one might argue that 100% emergence would be more suitable to include instead of 90% emergence, there were several days between the emergence assessment and the final plant count, which makes it unclear when precisely 100% emergence occurred. The final seedling emergence was specified as the 100% emergence level since these plants make up the final crop stand. The length of the emergence phase, thus the emergence uniformity, was determined using the GDD requirement between initial emergence and 90% emergence.

Emergence variability was computed by calculating the difference in plant numbers between replicates. The one replicate with the most emerged plants was subtracted from the replicate that had the lowest number of emerged plants for each day, eventually dividing this difference by the final seedling emergence to normalize the effect of the seeding rate (Eq. 2):

Em. Var = (Highest emergence – Lowest emergence) / Final seedling emergence (Eq.2)

3.6.2 Seed singulation

Seed singulation was conducted within the identical rows used to assess crop emergence, across all three seeding rates. The measurements were carried out using a folding ruler placed alongside each row. Subsequently, measuring the distance between individual plants. Seed singulation was quantified as the variation in horizontal distance between seeds (standard deviation), divided by the average seed-to-seed distance in the seed row (theoretical seed distance) using a well-known statistical metric, called the coefficient of variation (CoV) (Bund 2021) (Eq. 3). A lower CoV gives indications of a better seed singulation.

CoV = Standard deviation / Theoretical seed distance (Eq. 3)

The conditions for seed singulation measurements were found most favorable just before the two-leaf stage. As the wheat plant develops two or more leaves, it might have become more challenging to distinguish whether it was two individual plants or a single plant with multiple leaves. This difference could have been particularly difficult to differentiate at higher seeding rates when plants are positioned in closer proximity to each other. This is the reason behind the selection of different measurement dates between the two seeders, as they had progressed differently in development. As a result, measurements were conducted on September 29th in the precision seeding treatments and on October 2nd in the seed drill treatments.

3.6.3 Seeding depth

The seeding depth assessment was also conducted within the same rows used to assess crop emergence and seed singulation and was also calculated for all three seeding rates. To measure seeding depth, a digital calliper was used to obtain the precise distance between the center of the seed and the point at which the plant stalk began to show signs of greening. The assessment took place on October 10th, as plants were dug up and washed to facilitate a better assessment. Afterwards, plants were brought indoors, and seeding depth measurements were carried out the next day, on October 11th. During this assessment, all germinated and non-germinated seeds were also counted to get a better understanding of the germination rate in each treatment.

3.6.4 Plant development

The same plants dug up on October 10th to measure seeding depth were also utilized to determine the plant development stages on October 11th. To assess the development stages, Zadoks decimal scale was implemented (Zadoks et al. 1974). The development stages were further refined to provide a more detailed representation of the differences and variations among all treatments. The seedling stages and tillering stages were consequently subdivided into narrower intervals. For example, stage 12 was split into 11.5-12 and 12-12.5, and stage 21 was subdivided into 20.5-21 and 21-21.5. On October 22nd, plants were dug up and brought indoors for evaluation the second time. As the original seeding rows had been dug up during seed depth evaluation and in the initial plant development staging, grading sites were relocated forward by one to two meters, using the same row lengths, while remaining within the same seed rows. The third plant staging took place on November 12th. This third staging did not have the same interval as the first two, as plant development was slowed down due to decreasing temperatures. Grading sites were once again shifted forward by one to two meters, and plants were dug up and brought indoors for evaluation.

The rate of plant development was examined across four distinct periods, from 50% emergence to October 10th, October 11th to October 22nd, October 23rd to November 12th, and from 50% emergence to November 12th. To compute the plant development rate, the accumulated GDD within each period was divided by the number of developed leaves within the same period to get the phyllochron interval, which refers to the time between the appearance of successive leaves. A higher rate of plant development is thus equivalent to a lower phyllochron.

The standard deviation (SD) was used to calculate variability in crop phenological development among neighboring plants, on October 10th, October 22nd, and

November 12th. A lower standard deviation indicates for less variation, resulting in more neighbouring plants assessing the same development stage.

3.7 Statistical analysis

The statistical analysis was conducted using Minitab Statistical Software, version 21. A two-way ANOVA analysis was carried out, which included the factors of seed rate, seeding method, and block number, along with an assessment of the interaction between seeding rate and seeding method. The statistical analysis focused on the following response variables: difference in germination rate and final emergence, seed depth variability, emergence at three different points in time, emergence uniformity, plant development at three different points in time, plant uniformity at three different points in time, and the plant development rate at four unique time intervals. To evaluate the significance of the analysis, a significance level of 0.05 was applied. Post-hoc Tukey's test was used to identify precise distinctions among the various treatments when a statistical difference was obtained.

4. Results

4.1 Seeding depth

The precision seeder maintained a more consistent average seeding depth, ranging between 2.5, 2.2, and 2.3 cm, with outliers excluded, at the 50, 75, and 100% seeding rate respectively (Figure 4), showing a maximum difference of only 0.3 cm in average seeding depth between treatments. In comparison, the seed drill exhibited an average seeding depth of 4.8, 4.0, and 4.4 cm, with outliers excluded, at the 50, 75, and 100% seeding rate respectively, with a maximum difference of 0.8 cm in average seeding depth between treatments. The precision seeder´s average seeding depth was accordingly set roughly 2 cm shallower at all three seeding rates, and the intention was not for the precision seeder as a concept to be sown 2 cm shallower. Furthermore, the precision seeder demonstrated a significantly reduced variability in seeding depth, with a standard deviation of 4.1, whereas the seed drill showed a higher standard deviation of 9.8.

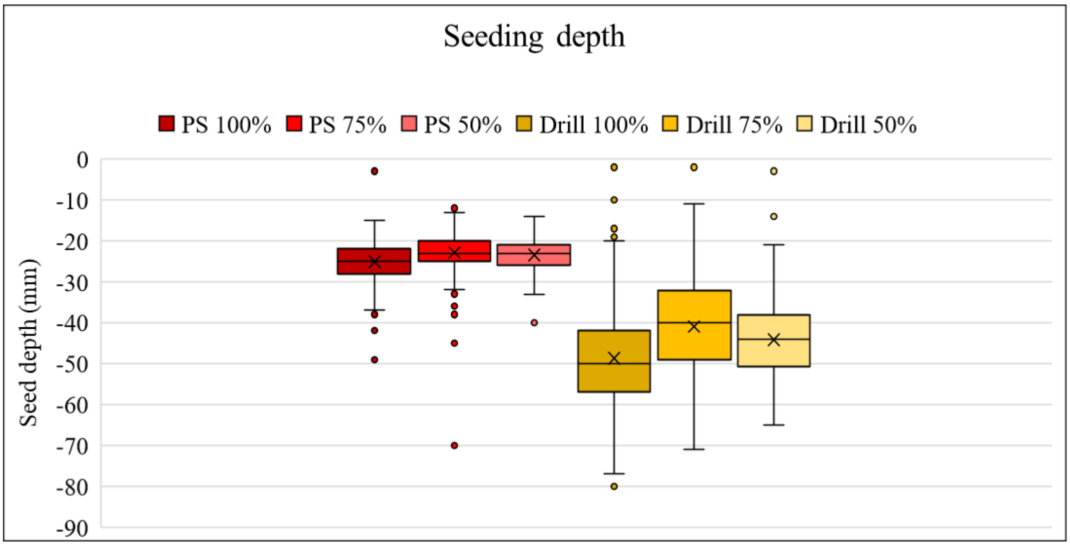

Figure 4. *Average seeding depth and seed depth variability at the 50, 75 and 100% seeding rate, comparing the precision seeder (PS) and seed drill (Drill). The coloured box represents 50% of the data, denoting the interquartile range (IQR), which extends from the lower quartile (Q1 or 25 percentile) to the upper quartile (Q3 or 75 percentile). Cross marks the average seeding depth in*

the coloured box and the centre line represents the median. Outliers marked with circles are values below Q1-IQR1.5 or above Q3+IQR1.5. The precision seeder had a standard deviation of 4.1 in seed depth variability whereas the seed drill showed a higher standard deviation of 9.8.

4.2 Seed singulation

The precision seeder demonstrated a lower coefficient of variation (CoV) at the 75 and 100% seeding rate, with values of 97% and 99% respectively (Figure 5). The seed drill showed a CoV of 100% and 123% at the 75 and 100% seeding rates respectively. However, at the 50% seeding rate, both seeders performed similarly with a CoV of 97%. Each bar is complemented by a numerical value, illustrating the average distance between seeds in the seed furrow, with variations between 1.1 cm and 5.5 cm (Figure 5). This variation is caused by differences in row spacings between the two seeders and the various seeding rates (Table 2). The wider row spacing in the precision seeder treatments explains the lower average distance between seeds in the seed furrow. Differences in average seed distance play an important role in the outcome of the seed singulation and complicate the comparison between treatments, something that will be further reviewed in the discussion.

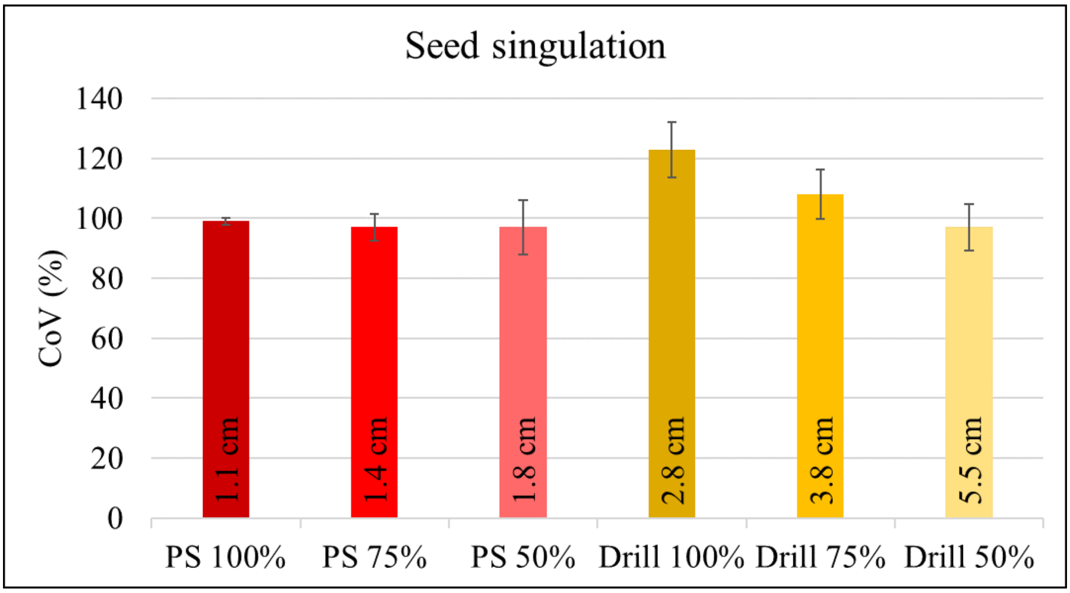

Figure 5. *Seed singulation at the 50, 75 and 100% seeding rate, comparing the coefficient of variation (CoV) between the precision seeder (PS) and seed drill (Drill). Numbers in bars refers to the theoretical seed distance between seeds in the seed furrow. Error bars display the standard deviation.*

4.3 Crop emergence

4.3.1 Targeted seed rate, seed germination, and final seedling emergence

The germination rate surpassed the targeted seeding rate in the precision seeder treatments, indicating that the actual seed output exceeded the targeted seeding rate (Figure 6). Conversely, a poorer germination rate relative to the targeted seeding rate was observed for the seed drill treatments. As no ungerminated seeds were discovered during the assessment of seeding depth, it could be inferred that the seed output in the seed drill treatments probably fell below the targeted seeding rate. Furthermore, when comparing the two seeding methods, the precision seeder exhibited a significantly higher emergence rate relative to the germination rate, indicating that more of the germinated seeds emerged in the precision seeder treatments. Consequently, the final seedling emergence in the precision seeder treatments reached 209, 330, and 403 plants/m^2 at the 50, 75, and 100% seeding rates respectively. Compared to the seed drill treatments that reached an emergence of 139, 219, and 277 plants/m^2 at the 50, 75, and 100% seeding rates respectively.

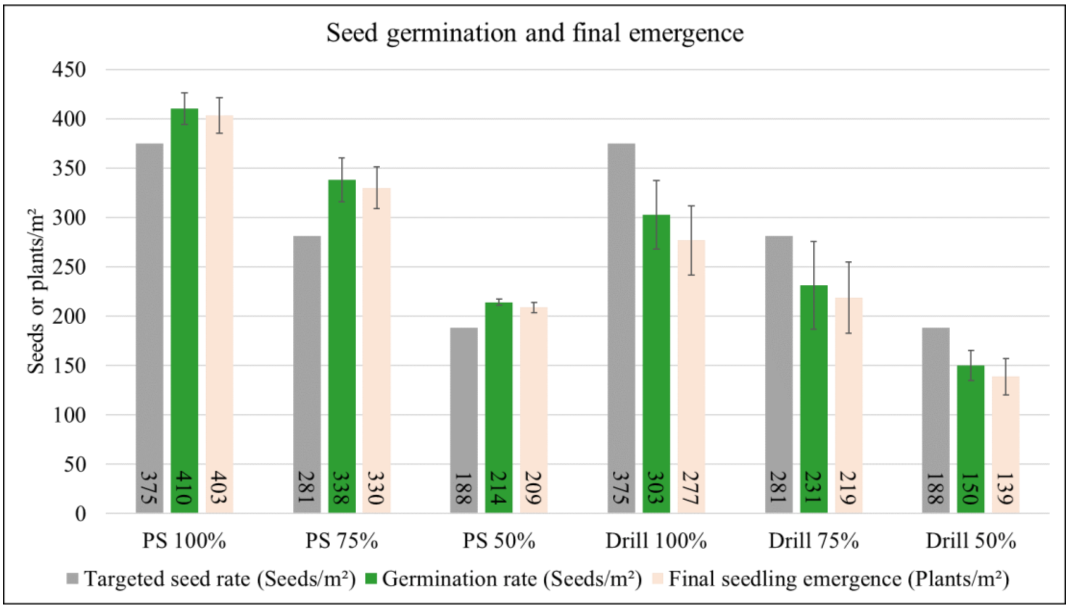

Figure 6. *Targeted seeding rate, germination rate and final seedling emergence at the 50, 75 and 100% seeding rate, comparing the precision seeder (PS) and seed drill (Drill). Numbers represent the value for each bar. Error bars display the standard deviation.*

4.3.2 Time of emergence and emergence duration

The precision seeder reached both initial, 50 and 90% emergence significantly faster than the seed drill (Table 3). Requiring 129, 163, and 183 GDD for initial, 50 and 90% emergence respectively, whereas the seed drill required 146, 170 and 193

GDD to reach initial, 50 and 90% emergence respectively. However, the precision seeder required more GDD between initial emergence and 90% emergence compared to the seed drill. This is also evident in Figure 7, where the precision seeder exhibits a gentler slope at all three seeding rates, implying for a more extended emergence phase. The seeding rate does not impact the time of emergence or the duration between initial emergence and 90% emergence significantly.

Table 3. *Growing degree-days (GDD) to initial, 50, and 90% emergence and duration of emergence (initial emergence -90% emergence) for the precision seeder (PS) and seed drill (Drill), for the parameters of seeding method & seeding rate, seeding method and seeding rate. Means in a column that do not share a letter are significantly different at the 5% level.*

	Initial Emergence	50% Emergence	90% Emergence	Duration of emergence
Seeding method & Seeding rate				
PS 100%	129 ^{A}	164 ^{A}	185 ^{A}	56 ^{A}
PS 75%	129 ^{A}	163 ^{A}	185 ^{A}	56 ^{A}
PS 50%	129 ^{A}	162 ^{A}	180 ^{A}	51 ^{A}
Drill 100%	152 ^{B}	172 ^{A}	193 ^{A}	41 ^{A}
Drill 75%	146 ^{B}	168 ^{A}	197 ^{A}	52 ^{A}
Drill 50%	141 ^{B}	169 ^{A}	189 ^{A}	48 ^{A}
Seeding method				
PS	129 ^{A}	163 ^{A}	183 ^{A}	54 ^{A}
Drill	146 ^{B}	170 ^{B}	193 ^{B}	47 ^{A}
Seeding rate				
100%	141 ^{A}	168 ^{A}	189 ^{A}	48 ^{A}
75%	137 ^{A}	166 ^{A}	191 ^{A}	54 ^{A}
50%	135 ^{A}	165 ^{A}	185 ^{A}	50 ^{A}

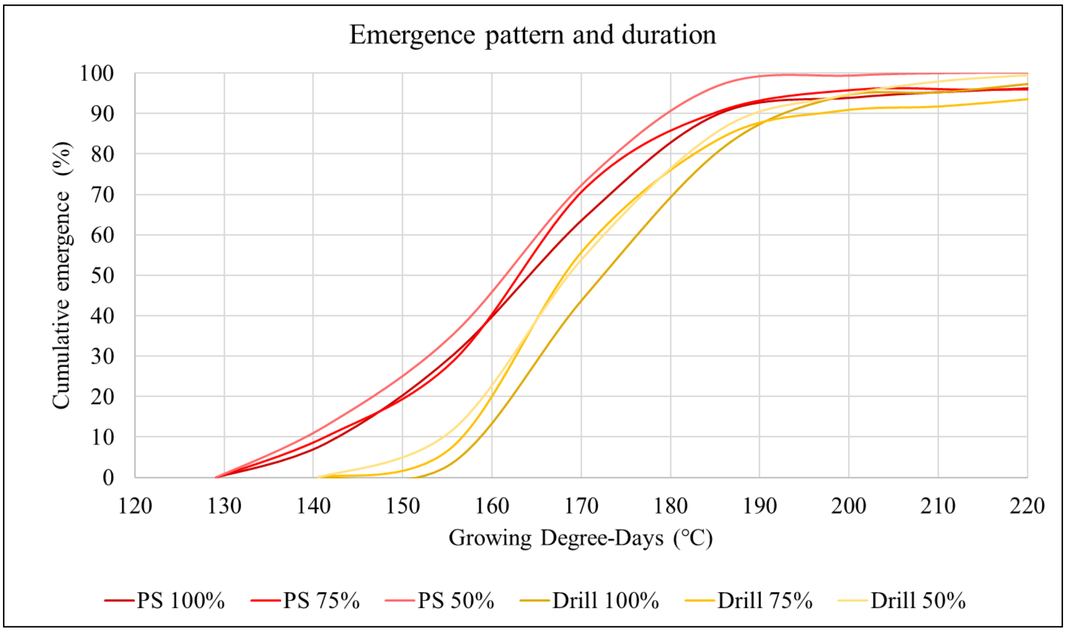

Figure 7. *Emergence pattern and duration at the 50, 75 and 100% seeding rate, comparing the precision seeder (PS) and seed drill (Drill).*

4.3.3 Emergence variability

Variability in emergence between replicates brings one additional aspect to the evaluation of the crop stand evenness. Throughout the emergence phase, the precision seeder demonstrated a reduced variability in the number of emerged plants between replicates (Figure 8). The seed drill displays an emergence variability as high as 45% at its peak, at the 50% seeding rate, while the precision seeder, at most, had an emergence variability of only 15% at the 75% seeding rate.

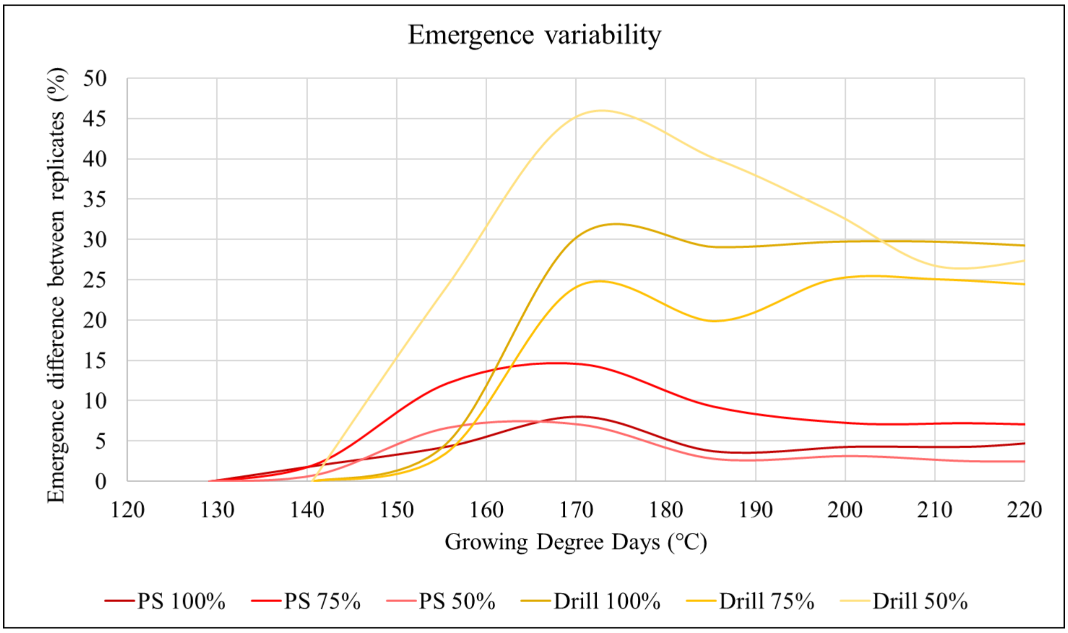

Figure 8. *Emergence variability during the emergence phase at the 50, 75 and 100% seeding rate, comparing the precision seeder (PS) and seed drill (Drill). The X-axis represents the replicate with the most emerged plants subtracted from the replicate with the lowest number of emerged plants, divided by the final seedling emergence for each treatment to normalize the effect of the seeding rate.*

4.4 Plant development

In order to evaluate the plants, they had to be dug up to differentiate among them. Consequently, a new location was selected in the field for each assessment as outlined in the methodology. This might have impacted the results since different plants were examined during all three assessments. The seed drill treatments were also sown one day later than the precision seeder treatments, but all six treatments were examined on the same day. This led to the precision seeder treatments having one additional day for leaf and tiller development.

4.4.1 Leaf and tiller numbers

The precision seeder treatments have been significantly ahead in both leave and tiller development the entire autumn (Table 4, Figure 9). As of the last plant assessment on November 12th, the precision seeder displayed an average tiller count of 1 per plant, whereas the seed drill had developed only 0.7 tillers per plant. A notable observation is the precision seeding treatment at the 50% seeding rate on November 12th. It exhibits a significantly higher number of tillers per plant compared to the seed drill treatments and significantly more tillers per plant than the 75 and 100% seeding rates sown by the precision seeder (Table 4). No significant difference was found between the three seeding rates. However, a lower seeding rate seems to have produced slightly more leaves and tillers compared to a higher seeding rate.

4.4.2 Plant stage uniformity

The precision seeder had higher variability in crop phenological development among neighbouring plants compared to the seed drill, but only with a significant difference on October 10th and October 22nd (Table 4). This is also evident in Figure 9, where the precision seeder displays shorter bars across more development stages. The seeding rate has not seemed to affect plant stage uniformity significantly.

4.4.3 Rate of plant development

The precision seeder displayed a significantly faster plant development rate between 50% emergence and October 10th, with a phyllochron interval of 68, compared to the seed drill at 74 (Table 4). However, between October 11th and October 22nd, no significant differences were observed between the two seeders. Yet, between October 23rd and November 12th, the precision seeding method experienced a halt in development, requiring a significantly higher phyllochron of 79 compared to the seed drill at 73. Throughout the entire autumn, from 50% emergence to November 12th, no significant differences were observed between the two seeding methods regarding the plant development rate (Table 4). No significant distinction in the rate of plant development was identified in the combination of seeding method & seeding rate or between the seeding rates.

Table 4. *Plant development for the precision seeder (PS) and seed drill (Drill), for the parameters of seeding method & seeding rate, seeding method and seeding rate. Average leave or tiller number and standard deviation (SD), on October 10th, October 22nd and November 12th. Phyllochron interval in growing degree days between 50% emergence-October 10th, October 11th-October 22nd, October 23rd-November 12th and 50% emergence-November 12th. Standard deviation illustrates variability in crop phenological development and phyllochron describes the development rate within each time period. Means in a column that do not share a letter are significantly different at the 5% level.*

	50% Emergence - 10 Oct			11 Oct - 22 Oct			23 Oct - 12 Nov			50% Emergence - 12 Nov
	Avg. Leaf No	SD	Phyllochron	Avg. Leaf No	SD	Phyllochron	Avg. Tiller No	SD	Phyllochron	Phyllochron
Seeding method & Seeding rate										
PS 100%	2.0^{A}	0.41^{A}	68^{A}	2.8^{A}	0.33^{A}	97^{A}	1.0^{A}	0.41^{A}	84^{A}	78^{A}
PS 75%	2.1^{A}	0.38^{AB}	68^{A}	2.8^{A}	0.31^{A}	97^{A}	1.0^{A}	0.39^{A}	81^{A}	77^{A}
PS 50%	2.1^{A}	0.35^{AB}	67^{A}	2.8^{A}	0.33^{A}	108^{A}	1.2^{B}	0.46^{A}	71^{A}	75^{A}
Drill 100%	1.6^{B}	0.24^{B}	72^{AB}	2.4^{B}	0.27^{A}	95^{A}	0.7^{C}	0.43^{A}	75^{A}	78^{A}
Drill 75%	1.5^{B}	0.24^{B}	77^{B}	2.4^{B}	0.27^{A}	95^{A}	0.7^{C}	0.35^{A}	72^{A}	77^{A}
Drill 50%	1.7^{B}	0.24^{B}	71^{AB}	2.4^{B}	0.25^{A}	100^{A}	0.7^{C}	0.41^{A}	73^{A}	77^{A}
Seeding method										
PS	2.1^{A}	0.38^{A}	68^{A}	2.8^{A}	0.32^{A}	101^{A}	1.0^{A}	0.42^{A}	79^{A}	76^{A}
Drill	1.6^{B}	0.24^{B}	74^{B}	2.4^{B}	0.27^{B}	96^{A}	0.7^{B}	0.39^{A}	73^{B}	77^{A}
Seeding rate										
100%	1.8^{A}	0.32^{A}	70^{A}	2.6^{A}	0.30^{A}	96^{A}	0.8^{A}	0.42^{A}	79^{A}	78^{A}
75%	1.8^{A}	0.31^{A}	73^{A}	2.6^{A}	0.29^{A}	96^{A}	0.9^{A}	0.37^{A}	77^{A}	77^{A}
50%	1.9^{A}	0.30^{A}	69^{A}	2.6^{A}	0.29^{A}	104^{A}	1.0^{A}	0.44^{A}	72^{A}	76^{A}

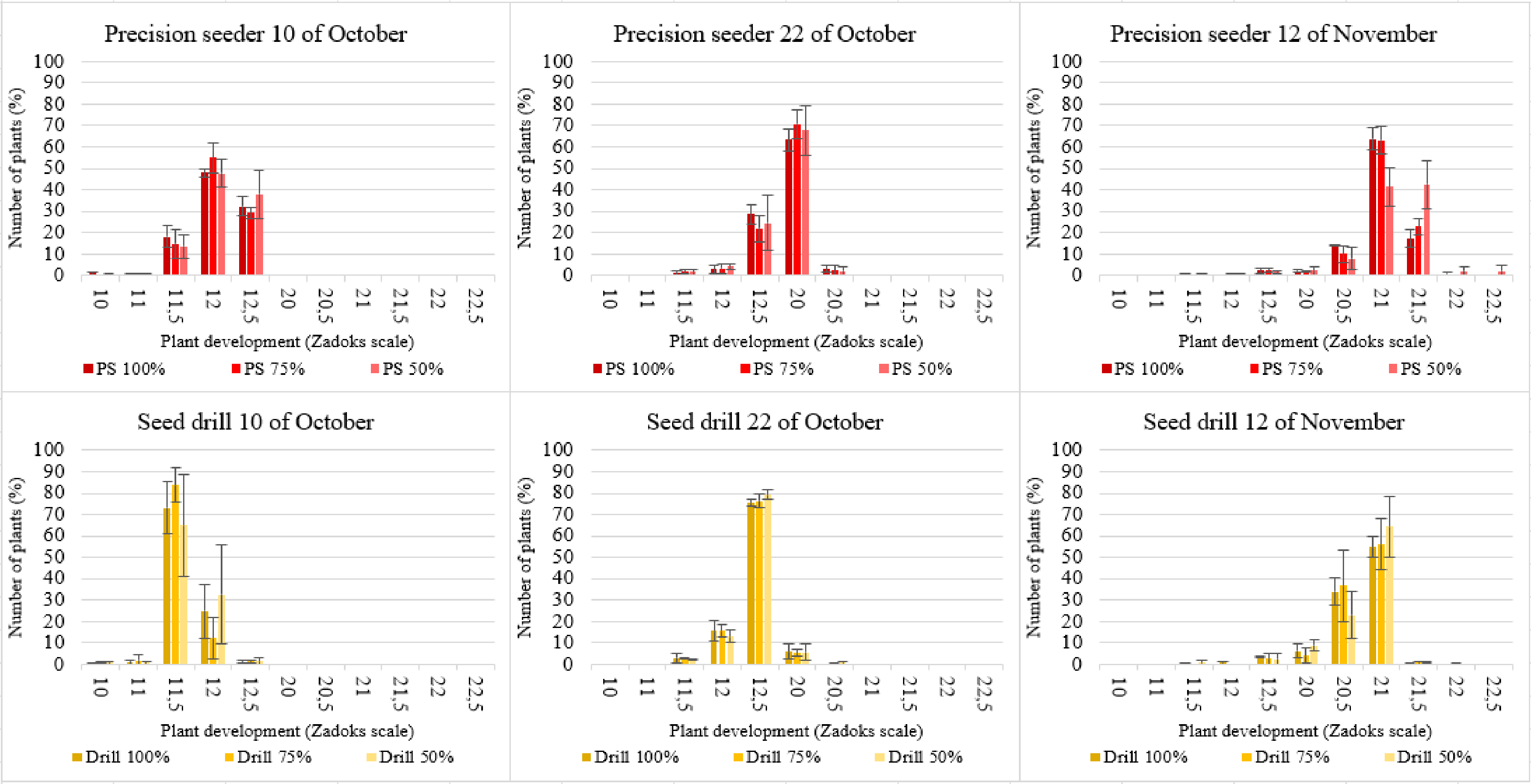

Figure 9. *Plant development on October 10th, October 22nd and November 12th at the 50, 75 and 100% seeding rate, comparing the precision seeder and seed drill. Error bars display the standard deviation.*

5. Discussion

This study aimed to investigate how precision seeding could improve winter wheat establishment. To achieve this, a field experiment was set up to compare a precision seeder prototype adapted for small grains, against a conventional seed drill. The field trial also included three different seeding rates, 375 seeds/m^2 (100%), 281 seeds/m^2 (75%), and 188 seeds/m^2 (50%), with field assessments overlooking the seeding depth, seed singulation, emergence, and plant development. As both seeders had different row spacings, fertilizer placements, sowing dates and average seed depth, this presented a challenge in assessing the impact of seed placement on emergence and plant development. This next section will thus attempt to establish connections and discuss the interactions between these differences, leading to the observed outcomes.

5.1 Seeding depth and crop emergence

Following the seeding process, the objective is to achieve a quick and uniform emergence to establish a uniform and competitive crop. During this phase, the interaction between soil temperature, soil-water content, and seeding depth plays a crucial role in achieving these objectives (Lindstrom et al. 1976; DeJong & Best 1979). Lafond & Fowler (1989) conducted a study investigating how soil temperature, soil water, seeding date, and seeding depth affected median emergence time, development, and cold tolerance of winter wheat under controlled laboratory conditions. It also included a rainfall simulation study to see the effects on temperature, seeding depth, and rainfall amount, including six temperatures (5, 10, 15, 20, 25, and 30°C), two seeding depths (1.8 and 3.6 cm) along with three simulated rainfall amounts (6, 9.3, and 12.5 mm). Under dry seedbed conditions, Lafond & Fowler (1989) discovered that a simulated rainfall of 9.3 mm after seeding is enough to ensure a successful establishment with a seeding depth of less than 2.5 cm. Since all treatments in this field study only received just over 6 mm after seeding, this may explain the poorer germination in the seed drill treatments due to the larger seeding depth (Figure 4, Figure 6). However, the autumn season experienced abundant rainfalls, 171 mm in August alone. The high precipitation levels indicate that the seedbed likely was in a moist condition, and the additional rainfall of 6 mm after seeding should have been sufficient to get seeds at larger depths to germinate in the seed drill treatments. However, the increased seeding depth could also have limited the access to oxygen and therefore caused a lower germination rate (Anderson & Garlinge 2000; Bremner et al. 1963), and considering the significant rainfall levels during the autumn, this impact is likely to be amplified. However, during the seeding depth assessment on October 10th, no ungerminated seeds were discovered, indicating that the seed metering might have provided a seed output lower than the targeted seeding rate in the seed drill treatments. The same holds for the precision seeder, although with a seed output higher than the targeted seeding rate (Figure 6).

A lower number of the germinated seeds emerged in the seed drill treatments (Figure 6). Hines et al. (1991) and Kirby (1993) suggested that this could be attributed to the larger seeding depth. A deeper placement of seeds increases the risk of the first leaf emerging underground, thereby lacking the rigidity to push through the soil surface like the coleoptile, something that also was noticed in this field study. Hadjichristodoulou et al. (1977) also saw a strong correlation between emergence rates and seeding depth, with deeper-placed seeds exhibiting a lower emergence rate. The larger seeding depth observed in the seed drill treatments (Figure 4) might thus account for the lower emergence level in relation to the germination rate (Figure 6).

During emergence, the precision seeder reached both initial, 50, and 90% emergence faster than the seed drill. The precision seeder reached these emergence points at 129, 163, and 183 GDD, compared to the seed drill that required 146, 170, and 193 GDD (Table 3). Thereby requiring an extra 7 GDD to reach 50% emergence compared to the precision seeder. Given that seeding depth is recognized for its significant impact on the time of emergence (Hadjichristodoulou et al. 1977; DeJong & Best 1979; Lafond & Fowler 1989; Kirby 1993), this becomes the most probable explanation for the precision seeder to reach both initial, 50 and 90% emergence faster than the seed drill. But, even though the precision seeder showed a significantly faster emergence, a more substantial difference was anticipated, given the shallower seeding depth (Figure 4). According to (Karow et al. 1993), a winter wheat crop requires 80 GDD for the seed to germinate and then an additional 20 GDD per centimeter of seed depth to emerge. This means that the precision seeder should have reached 50% emergence at 126 GDD with an average seeding depth of 2.3 cm, and the seed drill should have reached 50% emergence at 168 GDD with an average seeding depth of 4.4 cm. However, according to the study of Andersson (2016), there was only a one-day difference in reaching 50% emergence when the seeding depth was increased from 2 cm to 4 cm, aligning more closely with the findings of this study. Nonetheless, the smaller difference in the 50% emergence time between the two seeders can be attributed to multiple factors.

For instance, the precision seeder had a tendency towards a more open seed slot (Figure 10),

Figure 10. *Seedbed finish after seeding with precision seeder (left) and seed drill (right).*

which very likely was a consequence of the wet autumn and perhaps a slightly misconfigured seeder. The open seed slot probably caused a poorer seed-to-soil contact, subsequently reducing the imbibition of water between the seed and soil (John et al. 2011), thereby causing the seeds to either germinate at a slower pace or pushing the germination process forward in time until received precipitation after seeding. The precision seeder also exhibited a longer period between seeding and precipitation since these treatments were sown one day before the seed drill treatments, which further amplified the effect of a poor seed-to-soil contact, as the ungerminated seeds had one extra day without development. These two factors are the most probable cause of why the precision seeder did not reach initial, 50 and 90% emergence faster than it did.

The precision seeder did not improve emergence uniformity as the period between initial emergence and 90% emergence was longer, with a GDD requirement of 54, compared to the seed drill that only required 47 GDD (Table 3). A poorer seed-to-soil contact in the precision seeder treatments is once again the most probable reason, as this caused seeds to germinate at a slower phase or not at all until received precipitation, which dragged out the emergence phase. The earlier seeding of the precision seeder treatments aggravates the situation even more, as the duration between seeding and received precipitation was increased. However, the increased variability in seeding depth, present in all seed drill treatments (Figure 4), should have caused a more uneven emergence in these treatments, as seeds positioned at different depths exhibit different temperature requirements before emerging (Karow et al. 1993). This further suggests that the precision seeder likely would have attained a more uniform emergence without the drawback of a poorer soil-seed contact due to a lower seed depth variability (Figure 4).

Variability in emergence was significantly reduced through the utilization of the precision seeder (Figure 8). This reduced variability may be attributed to a more consistent average seeding depth (Figure 4), resulting in less variation in emergence dates within the field. But if this were the sole reason, variability would be near zero towards the end of the emergence phase, as all plants would have emerged by then. However, this was only the case for the precision seeder, thus hinting at the impact of an improved seed singulation, as plant densities remained more consistent regardless of the within-field location.

In conclusion, the precision seeder treatments exceeded the targeted seeding rate, while the seed drill treatments likely fell below the targeted seeding rate. Less of the germinated seeds emerged in the seed drill treatments due to a larger seeding depth. The precision seeder reached emergence faster than the seed drill, which supports part one of hypothesis 3: Precision seeding will ensure a faster crop emergence compared to conventional seeding. However, the shallower seeding depth is the most apparent cause for the precision seeder to reach these points of emergence faster. The precision seeder did not improve emergence uniformity, which relinquishes the second part of hypothesis 3, Precision seeding will ensure a more even crop emergence compared to conventional seeding. However, the precision seeder would likely have attained a more uniform emergence without the drawback of a poorer soil-seed contact since the seed depth variability was significantly reduced, which supports hypothesis 1: Seed depth variability will be reduced with the use of a precision seeder compared to a conventional seed drill.

5.2 Seed singulation

The use of the precision seeder led to an improvement in seed singulation (Figure 5). But the seed singulation got poorer at higher seeding rates, both for the precision seeder and the seed drill, a trend also observed by (Bund 2021). The fact that the seed singulation becomes poorer at higher seeding rates is also a mathematical issue since the CoV is calculated by dividing the standard deviation by the theoretical seed distance. This means that a change in seed-to-seed distance will exert a more noticeable impact on the CoV at a lower theoretical seed distance. Since the theoretical seed distance increases at lower seeding rates or wider row spacings, this complicated the evaluation. The wider row spacing in the precision seeder treatments (Table 2) decreased the theoretical seed distance compared to the seed drill (Figure 5), which increased the CoV without actually reducing the seed singulation quality. This phenomenon might also account for the greater gap in CoV among the seed drill treatments, as the theoretical seed distance varies more between each treatment compared to the precision seeder treatments, an effect caused by the narrower row spacing. This mathematical issue also makes it more challenging to compare results between studies, as the theoretical seed distance must be fairly similar. Despite this, both Bund (2021) and Canfield et al. (2019) showed in their respective studies that the seed singulation improved with the use of a precision seeder. Something that aligns with the results of this study. In contrast to the CoV, emergence variability offers additional insights into the evaluation of the seed singulation (Figure 8). Since the precision seeder exhibited a lower variability at the end of the emergence phase, this implies that the seed singulation was improved, as plant densities remained more consistent regardless of the within-field location.

To sum up, direct comparisons between treatments regarding the CoV may not be accurate due to variations in theoretical seed distance. However, considering that the precision seeder displayed a lower CoV despite a reduced theoretical seed distance at each respective seeding rate, one could argue that the precision seeder improved seed singulation quality at all three seeding rates. The precision seeder also showed a reduced emergence variability, which further supports hypothesis 2: Seed singulation quality will improve with the use of a precision seeder compared to a conventional seed drill.

5.3 Plant development

When examining the observed outcomes, it is essential to remember that all three plant assessments have been conducted in different locations within the field. The observations do not, therefore, consistently portray the development of the same plants throughout the autumn. This factor can undoubtedly have impacted the results, as both representative and less representative locations may have been selected within the field.

The precision seeder showed a significantly greater number of developed leaves and tillers throughout the autumn (Table 4, Figure 9). However, the prolonged development cannot be attributed to a faster development rate since the phyllochron interval was more or less the same for both seeding methods between 50% emergence and November 12th (Table 4). The greater number of leaves and tillers is much more likely an effect of an earlier emergence caused by a shallower seeding depth (Hadjichristodoulou et al. 1977; Kirby 1993; Andersson 2016). However, there were instances when plant development appeared to accelerate in the precision seeder treatments, while simultaneously decelerating in the seed drill treatments, and vice versa. The precision seeder demonstrated a significantly faster development rate between 50% emergence and October 10th. The presence of a starter fertilizer, mainly attributed to the nitrogen component could according to Steinke et al. (2021) help accelerate tiller production in the autumn. However, nitrogen absorption is constrained during the autumn, and a winter wheat crop usually does not take up more than 20 kg of nitrogen per hectare (Lindén 2000). But even lower nitrogen rates can contribute to promote the production of autumn tillers (Alley et al. 2009; Oakes et al. 2016). As of this, it was suggested that the starter fertilizer could have helped to accelerate plant development in the precision seeder treatments as it was seed-placed and not side-banded (Table 2), giving earlier access to the nutrients in the fertilizer. This is also consistent with the field observations, as the precision seeder treatments appeared greener and more vigorous after emerging. However, it is essential to note that these observations may also be influenced by the earlier emergence and further developed plants in the precision seeder treatments. From October 11th to October 22nd, all seed drill treatments also started to display indications of greening, possibly reaching the side-banded placed fertilizer. Nonetheless, there were no significant differences in plant development rate between both seeders during this period. During the last period between October 23rd and November 12th, there was a reversal in the plant development rate, with the precision seeder displaying a significantly lower rate instead. This could be explained by the higher plant densities in the precision seeder treatments, as a result of the higher seed output. This in combination with a wider row spacing contributed to an increased intra-specific plant competition within the seed row. The study of Gooding et al. (2002) shows that variations in seed density can impact winter wheat development. Higher seed densities often lead to a gradual reduction in the number of developed tillers per plant (Spink et al. 2000; Gooding et al. 2002; Tigabu & Asfaw 2016). The reduced development rate observed for the precision seeder could also be intensified due to a generally higher weed pressure, increasing the inter-specific competition (Figure 11).

Figure 11. *Winter wheat establishment at the 50% seeding rate, comparing weed pressure between precision seeding (right) and conventional seeding (left) on October 7th.*

The increased weed pressure could be linked to the precision seeder's lack of tillage during seeding. Weed control was also delayed because of the wet conditions in October, allowing the weeds to grow large. Even though the precision seeder displayed an overall reduced development rate between October 23rd and November 12th, it notably demonstrated the fastest plant development of all six treatments at the 50% seeding rate. Although not statistically insignificant, this suggests that the improved seed singulation could have gained greater significance as the theoretical seed distance increased, by reducing the intra-specific plant competition through a more uniform spacing between plants (Figure 12).

Figure 12. *Precision seeder with seed singulation. Results at the 50% seeding rate on October 10th.*

Similar results were found in the study of Bund (2021), as the yield benefits obtained through precision seeding were found to be restricted at a decreased theoretical seed distance, as a result of a higher seeding rate. When used at the 50% seeding rate, the precision seeder also displays a tendency towards a lower phyllochron interval when accounting for the entire autumn period, with a GDD requirement of 75 per developed leave, along with a significantly higher tiller number per plant on November 12th compared to the other five treatments (Table 4).

The uniformity of the plant stand has consistently favoured the seed drill over the precision seeder. This is evident in the lower standard deviation (SD) for the seed drill across all three plant assessments (Table 4). This trend is also illustrated in Figure 9, where the precision seeder displays shorter bars across more development stages compared to the seed drill. However, a significant difference between the two seeding methods was observed only on October 10th and October 22nd. The research by Gan et al. (1992) found that a uniform emergence leaves a crop stand with more equally sized plants. This was probably the case in this field study too, as the precision seeder treatments had a tendency towards a longer emergence phase, thus leading to a higher variability in crop phenological development, as plants initiated leaf development over a broader period.

The emergence variability can offer additional insights into the development of the plant stand composition (Figure 8). Given the lower variability attained with the precision seeder, it can be assumed that plants emerged in the same pattern regardless of the within-field position. Suggesting that the variability in crop phenological development also are more similar regardless of the within-field position, although plants in this composition may exhibit a broader range of development stages. This is also evident in Figure 9, as the precision seeder generally exhibits a lower and more stable standard deviation between treatments and over time. The plant density is also expected to stay more similar regardless of the within-field location due to the improved seed singulation, thus giving the same tiller density at any given position within the field.

It usually takes 100 GDD between the appearance of successive leaves of a winter wheat crop (Karow et al. 1993; Anderson & Garlinge 2000; Fowler 2018). This can however range between 75 and 120 GDD (Karow et al. 1993; Oakes et al. 2016; Fowler 2018). The chosen variety in the field trial was RGT Koi, showing a phyllochron between 75-80 GDD when accounting for the overall autumnal development (Table 4). Therefore having an excellent ability to produce many tillers per plant considering the general requirement of 100 GDD. Something that is advantageous for the precision seeder with a wider row spacing, as varieties with a lower phyllochron generally perform better than varieties with a higher phyllochron at a wider row spacing (Hussain et al. 2012).

All in all, the precision seeder stayed ahead in plant development throughout the entire autumn, most likely because of an earlier emergence. Despite the varying pace in plant development between the two seeding methods, no significant differences were found when accounting for the entire autumn period, therefore opposing the first part of hypothesis 4: Precision seeding will ensure a faster crop development compared to conventional seeding. But, when used at the 50% seeding rate, the precision seeder exhibited a significantly higher number of tillers per plant compared to the other five treatments on November 12th. This was believed to be attributed to an improved seed singulation, reducing the intra-specific plant competition. The precision seeder displayed a higher variability in crop phenological development, which relinquishes the second part of hypothesis 4: Precision seeding will ensure a more uniform crop development compared to conventional seeding. The underlying factor was believed to be caused by a less even emergence, caused by a poorer seed-to-soil contact.

5.4 Improvement potentials and future studies

When contemplating improvements for future research, it is crucial to determine whether the weight should be on investigating a seeding concept or individual factors such as the seed singulation and seed depth variability. In this experiment, two distinct seeding concepts were compared, each arranged with different fertilizer placements and row spacings. This complexity added challenges and complicated the evaluation of the seed singulation, emergence and plant development. Moreover, variations in average seeding depth and seeding date between both seeders further complicated the evaluation. Hence, if the field trial was to be repeated, to assess the sole impact of an improved seed singulation and reduced seeding depth variability on emergence and plant development, it would be necessary to restructure the experimental conditions. This involves minimizing the number of uncontrolled variables. Which includes maintaining a consistent row spacing between both seeders and using a broadcast spreader to distribute the starter fertilizer evenly across the field, enabling for a similar nutrient availability. If feasible, it is also crucial that all treatments are sown on the same day for a more reliable comparison between the seeders. It becomes equally important to have similar machine settings, including the average seeding depth and verifying an accurate adjustment of the seeding rate.

During this study, emergence was recorded when the seedling reached a height of five centimeters, which does not precisely align with other literature where emergence typically occurs when the seedling breaks through the soil crust, something to consider in future studies. Additionally, digging up seeds during germination could provide valuable insights into the emergence rate and emergence uniformity. Originally, the plan was to weigh the root biomass. However, the wet autumn and the likelihood that the high weed pressure had constituted to a more significant part of the biomass put this idea on hold, making it a prospect for future studies. It could also be interesting to evaluate the value of equally sized seeds, as several studies have shown that differences in seed size can influence emergence uniformity (Hadjichristodoulou et al. 1977; Gan et al. 1992; Aparicio et al. 2002; Chaichi et al. 2022). In this specific study, precision seeding demonstrated a tendency for a higher plant development rate at the lowest seeding rate. It would be interesting to explore this further by reducing the seeding rate even more or adopting a narrower row spacing. This could also be combined by testing different winter wheat varieties to understand which variety characteristics are best suited when utilizing seed singulation. Future studies could also explore the possible benefits of seed singulation in combination with plant growth regulators and fungicide applications, with the assumption that these management practices may be more responsive if precision seeding can offer less variability in crop phenological development within the crop stand.

6. Concluding discussion

Precision seeding shows promising findings to further improve winter wheat establishment, both through an improved seed singulation and reduced seed depth variability. However, the improved seed singulation does not appear to be that advantageous at higher seeding rates or wider row spacings, as this results in plants being positioned closer together within the seed row. The potential impact of even lower seeding rates or narrower row spacings could therefore be a prospect for future studies, anticipating that an improved seed singulation may result in an accelerated plant development when plants are positioned further apart within the seed row. Furthermore, to fully unlock the potential of a reduced seed depth variability, all seeds must germinate promptly upon seeding to achieve a uniform emergence and plant development. To ensure this, seeds should be placed at a depth with adequate soil moisture that applies to the entire field, along with a sufficient seed-to-soil contact. During this field trial, both seeders were configured with different row spacings and fertilizer placements, which implies that further research is required to better understand the sole impact of an improved seed singulation and reduced seed depth variability on emergence and plant development, but also their subsequent contributions to the final yield. Different varieties may be included in future trials to recognize which variety characteristics are best suited when plants are distributed more uniformly. A more uniform plant distribution might also affect the below-ground competition, making it interesting to study the root biomass response. Furthermore, in the pursuit of achieving a completely uniform emergence, the consideration of selecting seeds of uniform size is worth exploring. Future studies could also investigate the use of plant growth regulators and fungicide applications to further elevate the value of precision seeding, with the assumption that these management practices may be more responsive if precision seeding can offer less variability in crop phenological development within the crop stand.

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Populärvetenskaplig sammanfattning

Nya förbättrade jordbruksmetoder och innovationer har drivit avkastningsnivåerna av höstvete till nya höjder, vilket har säkerställt en riklig och pålitlig tillgång av detta viktiga baslivsmedel. Trots de betydande framstegen som har åstadkommits, börjar det finnas tecken på att skördeutvecklingen avtar runt om i världen. Denna stagnation är oroande med tanke på den ökande efterfrågan på livsmedel till följd av en växande global befolkning. Trots detta är det tydligt att det finns en större genetisk potential för ytterligare skördeökningar. Med ett växande intresse för precisionssådd av höstvete har nyligen genomförda studier visat att höstveteavkastningen kan ökas mellan 5% och 11% genom att använda specialdesignade såmaskiner eller såmaskiner anpassade för radsådda grödor, i syfte att replikera det potentiella resultatet med en precisionssåmaskin anpassad för spannmål. Precisionsådd skiljer sig från den konventionella såmetoden av höstvete genom att fröna i såraden kan placeras med ett enhetlig avstånd mellan varandra, också kallat frösingulering. En precisionssåmaskin är dessutom designad för att kunna bibehålla ett mer konsekvent sådjup. Flera maskintillverkare har börjat titta närmre på hur precisionsådd skulle kunna anpassas till höstvete, vilket i vanliga fall utnyttjas i grödor som kärnmajs och sojabönor. I nuläget finns det ännu inte någon precisionssåmaskin anpassad för höstvete tillgänglig på den öppna marknaden, men detta kommer troligen förändras inom en snar framtid.

Syftet med studien var att utvärdera om en precisionssåmaskin, specifik designad för spannmål, kunde förbättra etableringen av höstvete. Till skillnad från tidigare forskning, inriktades inte bara studien på utsädesplaceringen, utan också på dess effekter på uppkomsten och plantutvecklingen. Ett fältexperiment genomfördes därför i södra Sverige för att jämföra en precisionssåmaskinsprototyp mot en konventionell såmaskin vid tre olika utsädesmängder, 188, 281 och 375 frön/m^2. Grödetableringen utvärderades genom att analysera sådjup, frösingulering, uppkomst och plantutveckling.

Resultaten tyder på att precisionssådd kan bidra till att förbättra etableringen av höstvete, både genom en förbättrad frösingulering och minskad sådjupsvariation. Den förbättrade frösinguleringen antas dock inte bli lika fördelaktig vid högre utsädesmängder eller bredare radavstånd, eftersom detta resulterar i att plantorna placeras närmare varandra i såraden. Dessutom, för att helt utnyttja potentialen med en minskad sådjupsvariation måste samtliga frön gro direkt vid sådd för att uppnå en jämn uppkomst och plantutveckling. Under detta fältförsök var båda såmaskinerna konfigurerade med olika radavstånd och gödselplaceringar, vilket antyder på att mer forskning behövs för att få en bättre förståelse över den enskilda effekten av en förbättrad frösingulering och minskad sådjupsvariation på uppkomsten och plantutvecklingen, men också deras efterföljande bidrag till den slutliga skörden.

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