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Seed placement accuracy in cereals: Agronomic and economic capabilities of winter wheat in crop growth and yield formation at improved crop space homogeneity

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ANOVA .... *Analysis of variance*
CoV .... *Coefficient of variation*
DLG .... *Deutsche Landwirtschafts-Gesellschaft*
EMMEANS .... *Estimated marginal means*
FR20 .... *Test field France in year 2020*
GI19 .... *Test field Giessen/Rauischholzhausen in year 2019*
GI20 .... *Test field Giessen/Rauischholzhausen in year 2020*
ha .... *hectare*
HU20 .... *Test field Hungary in year 2020*
HY .... *Hybrid wheat variety*
ISO .... *International Organization for Standardization*
LAI .... *Leaf area index*
lm .... *linear model*
LMA .... *Leaf mass per unit area*
lmer .... *linear mixed-effects model*
NH .... *Non-hybrid wheat variety*
NIRS .... *Near infrared spectroscopy*
OS19 .... *Test field Oschersleben in year 2019*
OS20 .... *Test field Oschersleben in year 2020*
R:FR .... *Ratio of red to far-red light*
SP .... *Singulation planter*
SR .... *Seed rate*
Tec .... *Technique*
TKW .... *Thousand kernel weight*
TS .... *Test Site*
V .... *Variety*
VF .... *Variation factor*
VS .... *Volumetric seeding*

1. Introduction

With more than 220 million hectare in agricultural production, wheat is one of the most important crops used for food supply worldwide [2, 26, 88]. In the last years, several processes have been optimized to increase the average wheat yield production per area, like improving in-field farm management strategies and progress in breeding strategies with focus on increasing yield and grain quality parameters. In contrary, no significant yield increase per area has been observed during the last years despite the efforts of breeders and crop growers. For example, the annual genetic gain in wheat yield is on low level and estimated to range around 1 % [36, 41, 80]. Nowadays, most grain yield limiting factors are environmental and weather conditions during crop growth [64, 65]. It has been noted already that weather extremes and especially higher temperatures and droughts during vegetation periods are increased and prediction models deliver a trend that these extremes will be worse in the future [83, 104]. Therefore, an in-field plant population need to grow as efficient as possible to generate a stable yield production under changing weather conditions [65].

Moreover, the view on agricultural food production is enhanced, as especially the application of fertilizers and chemical plant protection is increasingly criticized due to its impact on environment and human health. As result, limitations and restrictions in applying fertilizers and chemical plant protection occur which can limit the production of high and qualitatively good wheat grain yields [99, 100]. Presently, the EU Green Deal foresees a reduction of 50 % chemical plant protection and 20 % less applied fertilizer until the year 2030 [19]. Because of that, a further agronomic optimization of farm management practices is required to be still able to produce sufficient and qualitatively good wheat yields [66].

Referring to winter wheat production, type of variety and the plant establishment in field can have an incremental role for a stabilized yield production. For example, hybrid wheat varieties are supposed to deliver higher and stable yields under changing and resource limited growing conditions compared to non-hybrid wheat varieties [52, 63, 75]. In addition, the nutrition efficiency of hybrid wheat varieties is mentioned to be higher while having also an increased resistance against crop diseases [71, 84, 89].

Focusing on the plant establishment in field, an optimized planting pattern of wheat plants can deliver additional potentials to increase the single plant use efficiency in terms of light, water and nutrients. When winter wheat plants are spaced in uniform tridimensional patterns, it has been observed that plants grow more efficiently compared to conventionally drilled plants, as the more homogenous plant pattern reduces the intra-specific competition, delivering an increased utilization of soil water and nutrients that stabilizes and/or enhances the yield production [54, 92]. In an agronomic point of view, more uniform seeding patterns are required to maximize the yield potential per single plant and thus per area [40, 53, 54,

76]. Besides yield effects, a more uniform seed pattern provides also the potential to reduce the plant population density in field. As winter wheat induces morphological changes in crop growth depending on intraspecific competition, plants adapt more efficiently the tiller and ear production if they are spaced more uniform at lower seed densities [54, 59, 92, 97, 100]. While the currently available seeding technique for cereals ensures a good seed placement in soil and a sufficient distribution quality of calibrated seed mass per area, these systems are not able to equally distribute the seeds within the trench [53]. Because of a volumetric seed dosage, followed by a random distribution of the seed mass flow to seed openers, the longitudinal seed distribution along the trench is characterized by bunch wise placed seeds [3, 30, 31]. As this is not reflecting the agronomic ideal of uniform seeding patterns, it is assumed that the use of a singulation planter can increase the plant distribution quality of wheat seeds [76, 92].
Taking these facts into account, it is worthwhile to follow a deeper analysis of the agronomic and yield effects when singulating winter wheat and how this is impacting the economic return for farmers, considering hybrid wheat varieties as well. Therefore, a field trial research was implemented to clarify the following hypotheses:

1. The use of a singulation planter in winter wheat is significantly improving the longitudinal plant space distribution quality compared to volumetric, random seed metering.
2. Seed singulation of winter wheat increases yield compared to volumetric, random seed metering.
3. Seed singulation of winter wheat maintains yield production at lower seed densities compared to volumetric, random seed metering.
4. Hybrid wheat varieties are outperforming non-hybrid wheat varieties in an agronomic perspective.
5. The use of a singulation planter generates higher revenue in hybrid wheat compared to non-hybrid wheat.

The observations and findings of this field trial research will be illustrated and explained below.

2. Literature

It is assumed that an increased crop space homogeneity reduces the intraspecific competition of the single wheat plants that deliver potentials of saving seed costs while increasing the yield. As this is affected by adapted plant growth reactions that depend on seed rate, seed distribution quality and also by crop variety, a detailed literature review of the specific crop growth reaction and the variety specific potentials of hybrid wheat is prepared upfront. In addition, a detailed view on the longitudinal seed distribution quality along the trench of currently available seed metering techniques and its evaluation methods is verified as well.

2.1 Morphological reactions on intra-specific competition in winter wheat

The crop growth and yield production of individual wheat plants highly depends on competition effects. Besides weeds as competitors, the intraspecific competition of wheat modifies the characteristics of the individual plants. Seed density is mostly influencing the competition, affecting an earlier start of competition for space, water and nutrients when higher plant densities are established in field [97]. Depending on available growing space, wheat plants respond with adapting number and size of their growing organs. Similarly, the distribution quality of the individual plants impacts the competition effects. For sugar beets and corn it is well known that an uneven plant distribution constrains the crop growth performance, as the increased intraspecific competition reduces the efficiency to take up the optimum amount of water and nutrients [33]. For wheat, several studies proved similar effects if the seeds/plants are placed in spatial uniform patterns [5, 51, 54, 95]. Nevertheless, the importance of seeding operation has low value for farmers concerning seed rates and timing [65], but optimizing the quality of seeding operation in terms of population density and quality of seed distribution can help to maintain wheat yield stability and to increase yield productivity, as a result of reduced intra-specific competition [51, 59, 92].

2.1.1 Root characteristics of wheat

A well-established root system is fundamental for the growing potentials of a single plant as it drives the acquisition of water and nutrients [18, 68]. Characteristic for wheat are 3-6 radicles that develop with profuse branching a deeper reaching, seminal root system. During tillering, the secondary root system (nodal roots) is developing (Figure 1) [37, 56]. Looking on the root system of wheat, different root characteristics and root architectural responses can be found between wheat varieties. Older wheat varieties tend to have deeper root development to ensure water usage out of deeper soil layers, whereas newer varieties are characterized by increased lateral root development in the upper soil layers to increase nutrient efficiency [22, 38, 79].

Indication for the variety specific root architecture is the seminal root angle (Figure 1). A narrow

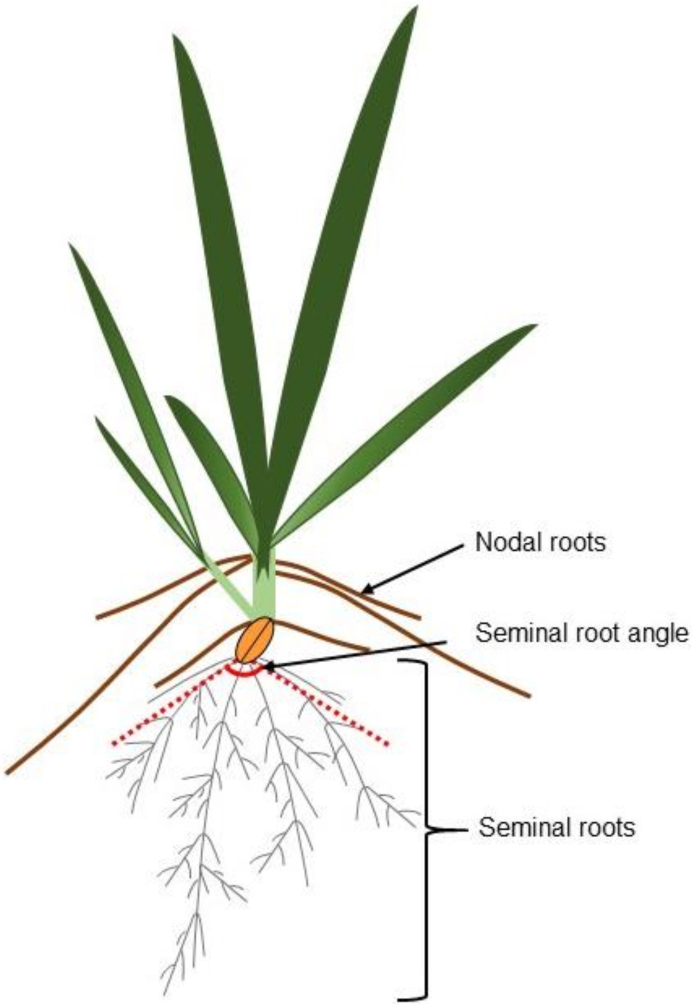

Figure 1: Winter wheat root characteristics (adapted from FRADGLEY et al. (2020) [79]).

seminal root angle creates a compact and deep root system while a wider angle of seminal roots creates a large but shallow root system [68]. Besides genetically driven characteristics of root development, agricultural practice methods influence root development too. For example, soil loosening due to tillage operations simplifies root growth caused by reduced penetration resistance of growing roots, resulting in deeper root growth and improved development of lateral roots [68, 79]. On the other side, high amounts of water and nitrogen in the upper soil layers inhibit root depth development [44]. The indication of sufficient soil resources reduces the power spent on root growth and development as this is costly for plant growth [22, 56], also larger soil water contents reduce the gas space in soil for oxygen causing stagnations in root growth [87, 105].

Plants in communities are competing to each other, aboveground reactions like shade avoidance strategy, adapting leaf orientation and shoot length are well known, whereas the reactions of root development are rarely examined as it is difficult to separate, identify and measure single roots of a plant [81]. Nevertheless, single plants compete for space aboveground for biomass development and below ground for root development to enhance uptake of soil resources. In soil, root exudates are used by plants as signaling components to detect neighbors [6, 9, 14].

While wheat is one of the worldwide grown major crops, less knowledge is available how the root architecture of wheat plants is influenced by competition within a wheat community [22]. An analysis, comparing the behavior of early root development and its interaction of wheat to wheat and wheat to blackgrass declared a greater reduction on root length in a wheat to wheat interaction. Combined with a high nutrient level a stronger reduction in lateral root development was identified. The reduced rooting depth due to a competing wheat plant affects tolerance to drought conditions. Furthermore the reduced number of lateral roots decreases water and nutrient uptake as they take up the resources in general more efficiently [22].

Another research, comparing the root architecture of different population densities in spring barley clearly demonstrated a significant modification in root system architecture if the plant density and thus the potential growing space per plant is changing. In higher population densities, plants reduced the investment into root biomass while enhancing the development of more fine roots in the upper soil layers. Differences in rooting depth were not detected. The tillering process is mentioned as one influencing factor as tillering is positively correlated to growth of nodal roots. At increased population densities, the higher competition reduces the tiller production per plant and thus the number of nodal roots. Therefore, the root length density in topsoil is increasing [38, 39].

Comparing the nutrient uptake, the nodal root system achieves a greater efficiency versus the seminal roots. This can be linked to a greater root volume per unit length of nodal roots. On the other side, seminal roots have a greater total weight that results in an increased absorption rate of nutrients, if nodal roots are not able to generate an efficient nutrient supply [55]. While the number of nodal roots is contributed to the tillering capacity, its development is highly impacted by changing plant population densities as the tiller production reacts on competing neighbors. In contrast, the seminal root structure is mostly genetically driven and remains unaffected when plant population densities change. The reduced number of nodal roots in high population densities reduces the nutrient availability for the individual plants but the increased population density reduces the amount of nutrients needed for the single plants as less tillers are needed to compensate the available growing space [79]. This reflects the adaption of plants to use the space as efficient as possible. Nevertheless, differences in nutrient uptake between seminal and nodal roots are existing, tending to a higher efficiency of nodal roots [22, 55]. After years of selective breeding for yield, the number of later developing roots and in particular nodal roots has been reduced. However, the understanding of the most beneficial root trait is still not fully understand and additional research is recommended to reflect also the root behavior under differing environmental conditions, tillage regime and sowing density [79]. At this point, potential effects of improved plant spacing on root development in field need to be considered. Bearing in mind, that the growth of nodal roots is positively correlated to tillering, higher plant competition lowers the number of tillers per plant and also the number of nodal roots. Hence it can be assumed, that lower plant densities and/or improved crop spacing homogeneity reduce the plant competition resulting in a higher tiller frequency and consequently in an enlarged number of nodal roots.

2.1.2 Plant growth effects and development of crop biomass

To ensure optimum crop growth, the below soil root system and the above soil biomass development are interdependent. While roots ensure the supply of water and nutrients for plant growth, the leaf mass of the plant generates energy sources through photosynthesis, that are used for producing additional biomass on the one side and to enhance root growth on the other side for efficient uptake of water and nutrients. It has been stated already that the root system of wheat plants adapt in terms of competition effects to neighboring plants but more obvious effects of adjusted crop growth reactions can be recognized during the development of crop biomass.

Plants detect competing neighbors due to intercepted radiation. Higher plant densities cause fundamentally changed differences in light quality as an increase of biomass absorbs more sunlight [97]. Driver is the ratio between Red and Far-Red radiation (R:FR) which is used as warning signal for plant competition [24]. During development of additional biomass, the R:FR shrinks as more red light is absorbed by pigments of the plants. Plants detect the change of R:FR by phytochromes and react with inducing morphological changes in crop growth [97]. Besides biomass development as influencing parameter, the R:FR ratio is also impacted by plant population density [43]. A higher density fastens the reduction of R:FR and plants start to adapt their crop growth towards increased crop height and reduced tiller formation. Focusing on the tiller production of wheat plants, several threshold values in light interception are identified where tillering stops. If the R:FR ratio reaches a level below 0.35-0.4, bud outgrowth for additional tiller formation is suppressed. In further development, cessation of tillering and thus outgrowth of fertile tillers depends on R:FR ratio and leaf mass per unit leaf area (LMA). A ratio of 0.25-0.3 R:FR is specified as threshold value where tiller appearance is ceased. The following bud outgrowth highly depends on the LMA, values below 3 mg/cm^2 reduce the probability for outgrowth and buds stay dormant. This reaction can be interpreted as association between parent leaf and bud, as there is a nutritionally dependency of the leaf above the bud [21].

The process of tiller formation influences yield production as it drives the final ear production. During tiller development, the individual wheat plant competes in resource usage between spike development which is determining the grain number per ear. Excessive tillering increases the competition for assimilates with the main shoot, increasing the risk of a lower yield production per area as grain number per ear and grain weight is reduced for each additional tiller [11, 34, 50, 73]. This reaction can be mostly seen in high population densities due to a higher tiller mortality rate. Unproductive tillers are inefficient plant material that waste plant growth resources, as just small parts of nitrogen and carbohydrates can be recovered and translocated from unused tillers into main shoot [103]. Within low dense wheat populations, the total amount of ears per area is slightly lower [7]. Therefore, an enhanced survival rate of tillers is contributed to a greater water use efficiency, availability of nitrogen and radiation absorption per single plant, resulting in a higher production and better partitioning of assimilates. This increases yield production per area as spikelet initiation, ear growth and grain number per ear is enhanced [103]. However, a sufficient number of ear bearing tillers is required because the number of ears mostly determines produced grain number and so yield production [34, 92, 103]. As tillering is in addition genetically driven and changing between varieties, the interaction between optimum plant density and tiller production can change [7, 21].

The recognition of light intensity and thus the adaption of wheat plants to competing neighbors visualizes the plasticity of wheat to react on available growth space, delivering potential for wheat to generate stable yields between 70-400 plants per m^2 [1]. When comparing biomass production of low and high wheat population densities after harvest, no significant differences in crop dry matter production can be found, which is reflecting the increased relative plant growth rate at lower densities [17]. The increased growth rate is a response to an improved space use efficiency per plant effected by better usage of soil nutrients and light radiation. Within the early growth stages, lower population densities are characterized by a lower green area index, therefore the photosynthetic capacity of the single crops is increased. Due to the lower leaf mass, radiation is more evenly distributed through the canopy, increasing the photosynthesis of the lower leaves to a maximum rate. Combining the higher nutrient availability with the higher photosynthesis rate per plant, phyllochrones (period of leaf appearance) are shortened affecting a higher leaf and tiller production per plant. Also, duration of tillering is increasing, resulting in a higher number of tillers per plant and a higher survival rate of shoots, achieving a compensation of biomass production per area comparable to larger population densities [103].

Similar reactions have been observed during the evaluation of wheat plant architecture in wide and narrow row spacings. Compared to narrow row spacing, wide row spaced wheat plants respond with a reduction of tillering and a lower green area index during early growth stages. While proceeding crop growth, no more differences of green area index between both row spacings could be found during flowering. The narrow row spaced crops produced more tillers per plant, therefore the upper four leaves of the wide row seeded wheat were significantly increased and so compensating the green area index. This indicates also the higher resource availability of single plants when seeded in wider rows and thus the adaptability of wheat plants to react on growth space [1].

To produce maximum grain yield per area, a sufficient development of biomass is required to produce enough resources and assimilates through photosynthesis. Larger amounts of biomass can increase the photosynthetic activity per plant and thus enhance grain weight. On the other side a higher amount of water is needed as more plant material needs to be supplied, which increases respiration losses [23, 27]. In high density populations, wheat plants produce in early stages of crop development larger amounts of biomass per area compared to low population densities [47, 103]. This leads to a higher and inefficient use of water and nutrients. Throughout the following growing period, a faster depletion of soil resources speeds up the crop maturation, as the assimilate supply of leaves and grain filling is competing. This causes a faster stop of grain filling, with the risk of lighter grains and a reduced yield potential per area [27].

Besides competing effects on tillering and development of crop biomass, wheat growth reacts significantly on crop height, depending on competition effects. This effect is another morphological adaption of crop growth inducing the shade avoidance strategy [97]. Instead of producing additional tillers within larger densities, an earlier beginning of stem elongation in combination with erect and grouped pseudo stems can be recognized [1]. Due to increased internode extension, shoot length is increasing, causing additional competition for assimilates and a higher risk for lodging [23, 103]. Shorter stems enhance the partitioning of dry matter to spike growth and compete less for assimilates. Plant breeders use the approach of shortening shoot length already to improve the use efficiency of assimilates. Due to a genetical induction of dwarfing genes into wheat plants, the final crop height can be reduced [34, 97]. When reducing the competition effects within a wheat population, lower crop heights can be promoted, improving the final grain yield as a result of more efficient assimilate usage.

Reducing plant densities can be an option to reduce the competition effects between wheat plants. Due to an improved resource efficiency, plants compensate through additional tiller and biomass production the area yield production. Comparable effects on crop growth reactions as seen in reduced plant densities can be achieved with more uniform plant patterns in field, because plants have their individual growth spaces instead of growing in bulks when drill seeded in rows. It has been observed that soil is faster and more evenly covered, and that Leaf Area Index (LAI) is much more homogenous distributed over the area compared to conventionally drilled plots. The less the variation of LAI over the area, the lower are the self-shading effects of plants and so the light absorption of the canopy increases [47]. Furthermore, the more uniform development generates a faster canopy closing [54] that can also be an important driver to increase competition against weeds.

Differing reactions of winter wheat on intra-specific competition demonstrate the potentials of compensating and adapting growing potentials on available space. Changes in population densities result in different light interception rates that are used as indicator to react on potential growing space. The higher the competition between plants, the more inefficient plant growth reactions like developing unproductive tillers, reduced radiation use efficiency due to shadowing of lower leaves and a wasteful partitioning of assimilates due to increased respiration losses can be detected. Reducing seed rates are an easy way to reduce competition between plants, considering that a higher accuracy of seed distribution over the area is needed to realize an efficient area usage with lower population densities. Based on the plasticity of winter wheat, plants react on available growth space especially with tillering, generating potential to fill gaps due to failures of seeding or damages by pests or diseases [97]. As commonly used technical seeding solutions for seed distribution of cereals are not able to generate an adequate inter row spacing of seeds, optimizations are needed to improve the quality of seed distribution when seed rates are going to be reduced.

2.2 Response of winter wheat to plant density and quality of seed distribution

In agricultural practice, winter wheat seed rates are mostly ranging between 300-400 seeds/m² [27, 76]. Reflecting to the plant physiological response of wheat plants in terms of growth space, lower population densities between 60-150 plants/m² has been reported to maintain the yield production compared to higher population densities [17, 27, 91, 103]. Prerequisite for lowering seed densities to these minimalistic rates are adequate amounts of water and nutrients and longer growing periods due to lower temperatures until grain filling [60]. The slower crop development within a longer growing season increases the time for individual plants to produce additional biomass, tillers and finally ears. These indications are valid when growing winter wheat in the continental climate of higher latitudes, like the north central parts of Europe.

Comparing this to Mediterranean growing conditions, characterized by mild winters with dry and hot summers, low seed densities result in yield losses. A shorter growing time due to warmer temperatures increases speed of plant development, with consequently less time for producing tillers and ears per single plant. At populations with 150 plants/m², an average production of two ears per plant could be found [60]. This won’t hit the requirement of minimum 400 ears/m² to produce the maximum yield per area [91], so the optimum density in Mediterranean conditions is mentioned to range between 400-500 seeds/m² while producing one ear per plant [60].

Based on these examples, the final ear density is highly important for yield production. Apart from environmental conditions, additional factors impact tiller and ear formation and so the potential of single plants to compensate on space. As lower plant population densities have the potential to maintain yield production, it is worthwhile to consider aspects driving the agronomic optimum plant density and the additional agronomic potentials of lower plant densities and how improved plant space quality can enhance these effects.

2.2.1 Agronomic optimum wheat population density

The optimum wheat plant population density is varying but can be estimated depending on a classification in yield environments. Low yield environments are characterized by low availability of water and nutrients, reducing the ability of producing tillers and finally ears per plant. In contrary, plant growth is more efficiently when soil resources are not limited like in high yielding environments that enhance the potential to compensate growing space with increasing the number of produced ears per plant. Consequently, an agronomic optimum plant density of 141 plants/m² is stated in high yield environments while low yield environments require 397 plants/m² to achieve highest yield production [7]. This fits to the previously described examples, comparing the environmental effects of temperatures and growing time between Continental and Mediterranean climate conditions. Lower temperatures in Continental climate zones slower crop development and increase the thermal time to full vernalization [91]. The availability of water and nutrients is mostly not limited and low densities of 100-150 plants/m² can then be compensated by increased tiller and ear formation per plant [27, 103]. While warmer temperatures in Mediterranean climates fasten the speed of crop development, the time for producing additional ears per plant is reduced and so the potential to compensate space. Under these conditions, seed rates need to range above 400 seeds/m² in order to produce a sufficient number of ears per area. [60].

In addition, time for crop development depends on seeding time. Later seeding dates reduce the time for crop development and so lowering the time for crop growth and tiller formation [7, 91]. Hence, later seeded plants have a reduced potential to compensate growing space, requiring higher seed rates to produce a sufficient number of ears per square meter [7, 91]. As an example, it is mentioned for winter barley that each delayed week of seeding requires 11.2 plants/m² more [38, 39].

Different characteristics of wheat varieties are another driver for the agronomic optimum seed density and final ear production. The potential of producing tillers and finally ears per plant to compensate on space is genetically driven and differs between varieties [7, 60]. A lower variety specific capability to produce tillers effects a more sensitive reaction on population density [7]. Besides ear density, grain number per ear and grain weight drive the final yield production. To compensate on yield production, these three components are influencing each other [103] and the right balance is needed to achieve highest yield production [17]. Greater ear densities reduce the number of grains per ear and can reduce the grain weight [91]. While the interaction between ear density and grain number per ear are typical observations, the effects on grain weight has less variation in terms of plant and ear density. Grain weight is more influenced by environmental conditions and wheat variety [60]. Nevertheless, slightly higher grain weight and grain number per ear can be observed at lower plant densities but these effects can not compensate a too low number of ears per area [17]. This underlines the importance of a sufficient ear density for maximum yield production.

To sum up, the agronomic optimum plant density highly depends on the potential of single plants to compensate growing space through producing additional tillers and ears. Depending on variety specific tillering potential, soil resource availability during tiller formation and growing time, influenced by climatic conditions and time of seeding, the optimum seed density need to be determined on these facts.

2.2.2 Potentials, challenges and risks of high and low seed densities

The continental climate conditions in the North Central European parts are ideal conditions to establish high yielding winter wheat populations in field. Under these conditions, 100-150 plants/m² are reported as the economic optimum density for seeding wheat. Nevertheless, seed rates of 300 seeds/m² and more are recommended [27]. Reason for high seed densities are better suppression of weeds [91] as the ground coverage is improved [60]. In addition, higher seed rates are used to decrease the weather related production risk [7], if the conditions in spring are not beneficial for tiller formation and thus space compensation with more ears per plant. For economic aspects it is worthwhile to use higher seed rates as the seed costs reflect only 19 % of the variable costs when growing wheat [91].

However, several agronomic potentials are stated when reducing the plant density to a lower optimum rate. Besides a reduced seed emergence at higher seed rates [103], increased plant losses over winter can be seen at higher population densities [91]. The higher plant competition at early crop stages causes a more rapid growth rate affecting that the reproductive apices are more exposed to frost. In addition, the accumulation of nitrogen and potassium per single plant is reduced compared to low seed densities. This reduces the frost resistance of the plants with a subsequent higher risk of frost damage or plant losses [102]. Also, the risk for lodging increases with greater plant densities as the plants tend to grow taller while producing thinner stems [27, 58].

These risks can be reduced with lower population densities. Besides that, plant growth efficiency is greater at lower densities. During resource limited conditions, a lower number of plants per area compete for the same amount of resources [7]. As a result, the tiller survival rate per plant is higher at low plant densities [27, 91, 103]. The larger ratio of dying tillers in high population densities can be regarded as waste of resources, as the in plant mass converted nutrients of dying tillers cannot be fully translocated into the surviving tillers [103].

Reduced winter wheat plant densities can maintain the yield production compared to higher densities. Due to the improved resource availability the risk of an uneven crop maturation can happen as the tiller production can proceed until ear emergence [27]. This increases the risk of lower Hagberg falling number, reducing the grain quality. In contrary, a higher depletion of water and nutrients in high seed densities leads to a more even crop maturation. Considering also a higher risk for lodging in high seed densities, the risk for a low Hagberg falling number is also high if the plants start to lodge [27].

Under continental climate conditions, potential is given to reduce the wheat plant density in field while maintaining yield production. Due to the low impact of seed costs and also the risk aversity of farmers the use of higher seed densities is mostly seen as low cost insurance if plant losses occur. However, improved resource efficiency, less plant losses during early crop growth and reduced risk for lodging are benefits for lower plant densities. If plant densities are going to be reduced the importance of plant space distribution is increasing to fulfill a more efficient area usage.

2.2.3 Agronomic potentials of improved crop space homogeneity

The plasticity of winter wheat to adapt crop growth potential and yield production demonstrates the opportunity to reduce population densities in field. Typically used seed rates range between 300-400 seeds/m² to ensure a homogenous plant coverage in field, whereas potentials are given to reduce population densities down to 60 plants/m² while maintaining yield if placed in more uniform patterns [1]. These low rates should not be in scope as they increase the risk of yield loss due to no emerging seeds or plant losses. In other researches, seed rate reductions down to 150-180 seeds/m² has been notified to be able to maintain or increase wheat yield production, when seed placement is improved [54, 100]. If seeds are more uniform placed, wheat plants will be later effected due to intraspecific competition [54], resulting in a better crop growth performance [33]. The single plants can use light radiation, soil water and nutrients more efficiently, resulting in a homogenous development and faster canopy closing [54]. This can be important in regions with restricted herbicide usage and/or herbicide resistances as the faster canopy closing increases weed suppression [47, 54, 96]. Additionally, phytosanitary advantage of lower plant densities and improved crop space homogeneity is given, as there is a higher air flow between the plants, causing faster drying of the canopy and reducing the risk for disease development [100]. The reduction of wheat plant population densities while improving seed spacing generate an economic value for farmers due to saving of seed costs and potential to increase yield production. Additional economic and sustainability effects can be reached at the same time based on reduced input usage of plant protection and fertilization [99, 100].

All in all, the agronomic benefits visualize the potentials of improved plant spacing and also in combination with lower seed densities. Nevertheless, there is still a lack of knowledge given, proofing the constancy of these effects under different growing conditions. To get a better understanding of these effects in winter wheat, additional insight generation is needed.

2.3 Hybrid winter wheat varieties

Breeding of hybrid varieties has potential to improve the agronomic traits of plant varieties [71]. This kind of breeding technology crosses the genetic pool of two different cultivars of the same plant species, using the effect of heterosis that is particularly pronouncing the efficiency of the next crop generation, mostly resulting in improved and stabilized yield production. Hybrid breeding is a typical form for open pollinating crops like corn, canola and rye, as the crossing of two varieties is easy to realize. Most cereals, including wheat, are autogamous crops. These characteristics affect a challenge to implement hybrid breeding in wheat. Additionally, the gene pool of autogamous crops is more homogenous than from open pollinating crops and reducing the heterosis effects. Despite these facts, hybrid wheat varieties are implemented to market as they have advantages in plant growth performance in terms of viability, growth and productivity [90].

Compared to pure line varieties, hybrid wheat increases the yield production in average up to 10 % [35, 63, 84, 89] with the side effect of stabilized yield production in marginal locations [62] or during stressful conditions because the tolerance to diseases, stresses and herbicides tends to be lower [89]. Especially in areas, that are highly influenced by drought conditions, the yield stabilizing effect due to heterosis is higher in contrast to areas with favorable growing conditions [75, 84].

The effect of grain yield heterosis in wheat is related to the heterosis of biomass [84], indicated by a faster crop development and biomass production during early stages of crop growth [52]. Due to the higher amount of biomass, hybrid wheat plants profit from improved light interception and thus radiation use efficiency. Also, better source-sink relations and greater assimilation rates during post-anthesis are reported for hybrid wheat plants. The combination of these parameter result in a greater assimilate supply during grain filling and thus improving the yield production [52].

Besides heterosis in aboveground traits, higher levels of heterosis were found for the root system [90, 98]. Compared to non-hybrid wheat varieties, hybrid wheat shows better performance in root development, including root length, root surface area, root biomass and root volume. The combination of enhanced root growth and larger root systems improve the acquisition of water and nutrients and thus enhancing the ability of hybrids to buffer water and/or nutrients if limited [98]. Contributing to root heterosis, higher accumulation rates of the protein alpha-tubulin has been found in hybrid wheat. It is assumed, that alpha-tubulin positively affects root growth and morphology [90].

Hybrid wheat varieties are still a niche product. So far, 1 % of the worldwide cultivated wheat area is seeded with hybrid wheat [71, 84, 89]. Breeding of hybrid wheat is cost effective and actual costs of hybrid wheat seeds are still not competitive against non-hybrid wheat varieties [63]. Agronomic potentials of hybrid wheat are given, but the heterosis effect in yield production is too low for compensating the higher seed costs [84]. To increase the economic value and adaption rate of hybrid wheat, production costs of seeds need to be reduced and/or higher yields are necessary to offset the higher seed costs [89]. So far, a cost reduction in breeding hybrid wheat seems not to be realistic [63], but new hybrid varieties with increased economic competitiveness are expected within the next 10-20 years [35, 89]. In terms of proceeding climate change and expected increasing water limited periods during crop growth, the role of hybrid wheat varieties will become more important due to the stabilized yield production compared to non-hybrid wheat [71, 75]

The advantage of hybrid wheat varieties highly depends on the agronomic management, including seed density, target grain quality and fertilizer strategy [84]. As cost reduction of hybrid wheat seeds seems not be realistic [63], the higher seed costs will inevitably lead to lower seed densities to realize comparable economic potentials to non-hybrid wheat varieties [52]. Based on recommendations from plant breeders, seed rates of hybrid wheat varieties need to be reduced to be economic competitive against non-hybrid varieties. When exceeding seed rates of 150 seeds/m², the profitability of hybrid wheat is reduced as the higher seed costs cannot be compensated through additional yield [85, 86].

To conclude, the profitability of hybrid wheat is too low as the potentially higher yield production is still not able to compensate the higher seed costs of hybrid wheat. As the profitability is mostly given at seed rates below 150 seeds/m², the importance of a qualitative higher seed distribution in field is consequently increasing as this can improve the area-use-efficiency of the individual plants and thus enhancing yield production. Currently used seeding techniques are not able to deliver an adequate plant distribution quality, so technical solution that improve seed spacing quality in trench like a singulation planter can be a solution to increase the efficiency and potentials of hybrid wheat varieties in field.

2.4 Seed application concepts in agricultural practice

When executing the seeding operation in field, farmers set the baseline for the upcoming crop growth period. Therefore it is important to ensure a good and equal plant establishment in field as this has incremental effects on the following crop development and yield production [30]. Driver for a good seed emergence and early crop growth are soil roughness, water availability, temperature, seed depth and even seed placement quality in soil. To reach these conditions, farmers typically execute several tillage passes upfront seeding. While seeding it is important to guarantee an equal seed depth and seed to soil contact within the trench. Besides a good seed placement in the soil, the seed distribution quality is key role as well. In an agronomic point of view, uniform seed and plant distances should be realized within the trench [33, 76]. Nonetheless, the typically used volumetric seed drills are not able to distribute the seeds in a uniform pattern [31, 76]. Several concepts were tested already to improve the in-row plant spacing of cereals but based on the higher seed densities of cereals there are still limitations given by slower driving speeds and row spacings which is also challenging the economic value of these systems [31, 76].

2.4.1 Volumetric seed metering

Volumetric seed metering is the state of art for seeding small grain seeds and in particular cereals [12, 61]. The idea of dosing seeds in defined volumes is not new and has been adapted already since the 18th century [53]. So far, the volumetric seed metering is an easy to realize and low-cost option to dose seeds while seeding and distributing them across large working widths [3].

Two types of volumetric seed metering are used, they can be separated between mechanic-gravimetric single row dosage using one metering unit per seed opener or into central dosage, distributing the seeds through an pneumatic air stream from one metering unit to all seed openers (Figure 2) [40, 53]. Besides differences in seed distribution quality across the work width [40], both systems have similar characteristics when focusing on the seed spacing quality within the trench, defined as longitudinal seed distribution. The volume-based dosage using cell wheels is not able to dose single seeds, resulting in typically bulk wise placed seeds in the trench with larger distances in between. When evaluating the seed distances in the trench and bringing these data into a histogram, the volumetric seed metering is characterized by a curve, following an exponential function (Figure 3) [30, 31, 33, 53]. A minor ratio of seeds placed in the target distance and high ratio of seeds spaced to close to each other is indicating the uneven longitudinal seed distribution.

Several concepts were tested already to improve the seed spacing quality of volumetric seed drills. Examples are the Reguline-System, the use of a Cascade-Opener and the Horsch Singular System. Tests declared significant improvements in seed spacing quality but high complexity and sensitivity of these systems in terms of seed mass flow, seed size and also limitations in driving speed prevent an integration of these concepts into agricultural farming processes [53, 70, 77, 100].

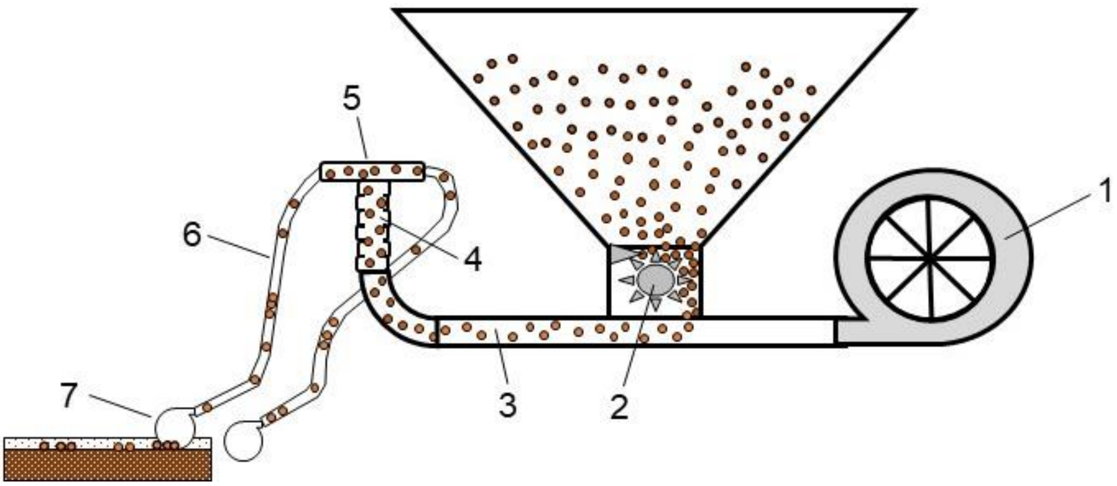

Figure 2: Pneumatic-volumetric seed distribution with fan (1), seed metering (2), delivery line (3), corrugated tube (4), distribution head (5), seed tubes (6), seed opener (7) (adapted from WEISTE (2015) [101]).

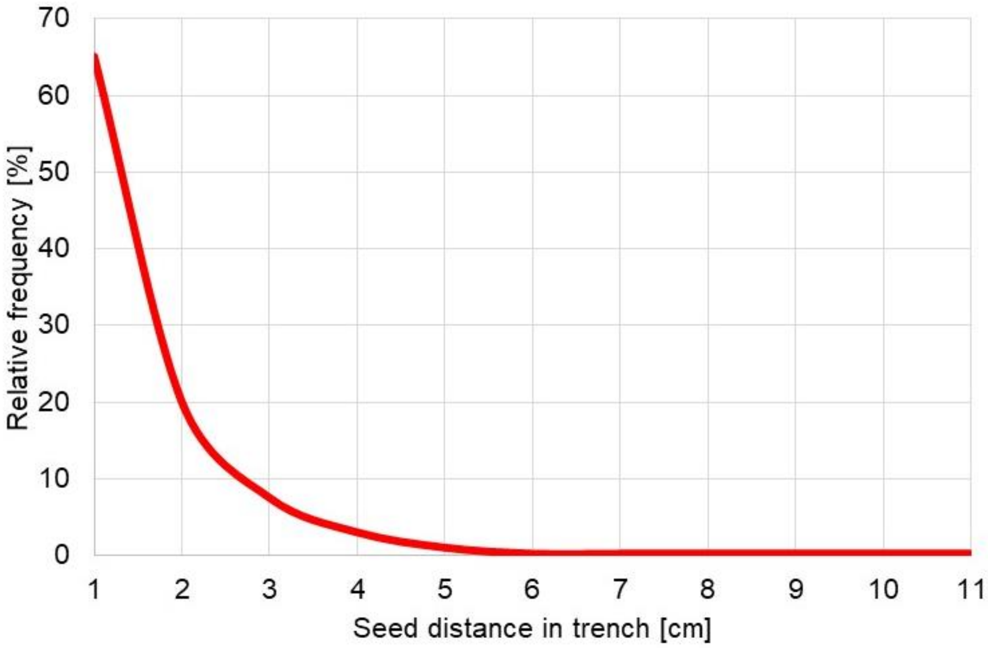

Figure 3: Seed distribution of volumetric drill seeding (Coefficient of variation ca. 100 %). (Based from MEINEL (2019) [53, 70]).

2.4.2 Singulation seed metering

Compared to volumetric seed metering systems, singulation seed metering improves the longitudinal seed spacing quality in the trench. This kind of metering system is characterized by single row metering systems but instead dosing the seeds on volumetric base, the seeds are picked up individually by a singulation device (Figure 4). Unlike volumetric seed drills, seed spacings are maintained equally [61]. When visualizing the seed spacing data of a singulation planter in a histogram, a normal distribution indicates the improved seed spacing quality with small deviations around the average (Figure 5).

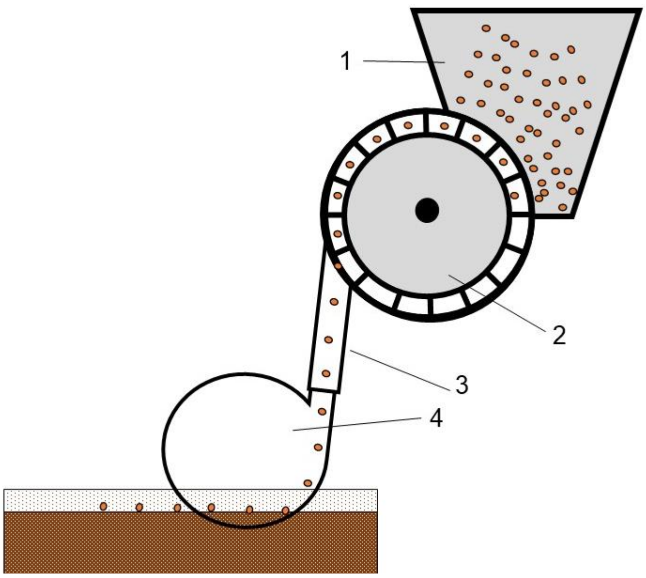

Figure 4: Seed singulation row unit with hopper (1), singulation disc (2), seed tube (3) and seed opener (4). (adapted from FIELD & LONG (2018) [61]).

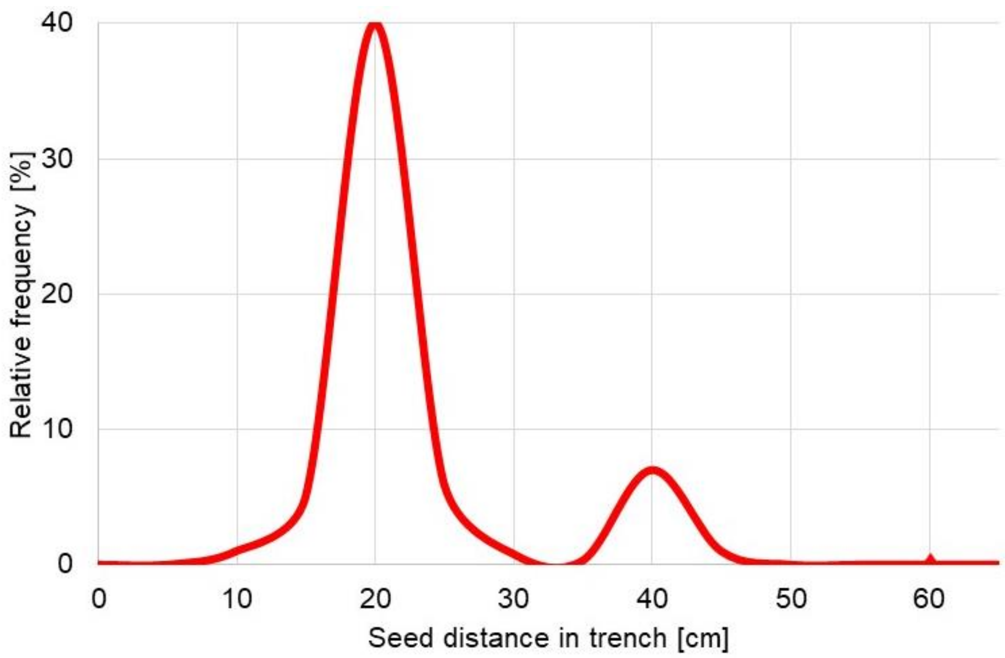

Figure 5: Seed distribution of singulated seeding (Based from MEINEL (2019) [53, 70]).

This fits the agronomic needs of defined single plant spacings in the trench to generate maximum crop yield production. Singulation planter systems deliver a high precision seed placement within the trench but mainly in row crops with lower seed densities like corn or sugar beets [61].

Pneumatic singulation systems for cereals have been successfully tested for a longer time, but first available machine designs have been brought to market in 2019 [74]. Even though the longitudinal seed distribution of cereals can be increased with this planter, low driving speed and machine based high row spacings of 25 cm are still obstacles for a successful market implementation.

2.4.3 Seed spacing quality in cereals: Technical obstacles

To increase and stabilize the area yield production of winter wheat, a reduction of intraspecific plant competition as a result of improved plant spacings is required to maximize the productivity and efficiency of the single wheat plants [30, 31, 76]. Due to the random seed distribution of commonly used volumetric seed dosage, potentials are given to improve the quality of seed spacings in trench. Since the beginning of the 20th century several machine forms have been tested to implement a high precision seed singulation of cereals. The most adequate method to singulate cereals has been realized with the usage of a planter design with vacuum singulation [76]. However, none of these methods has been successfully integrated to market yet, as driving speeds, row spacings, and handling of these machine forms do not fulfill farmers expectations.

Due to the low seed densities of corn and sugar beets, ranging between 6-12 seeds/m², the use of singulation metering systems is easier to realize compared to wheat with seed rates ranging mostly above 300 seeds/m² [76]. The higher the seed rate, the lower is the interrow distance of the seeds as a larger number of seeds need to fit into the trench. Similar effects can be seen if the row spacing is getting wider while using the same seed rate [33]. Despite the usage of narrower row spacings in cereals, the seed frequency per opener is 4-5 times higher compared to corn or sugar beets. For example, when seeding wheat with 300 seeds/m² at 15 cm row spacing and an operating speed of 12 km/h, each opener needs to place 150 seeds with a seed spacing of 2.2 cm within 1 sec. Compared to corn, seeded at 75 cm row spacing and a population density of 12 seeds/m², there need to be 30 seeds/sec placed at a seed spacing of 11.1 cm. The high seed frequencies of wheat combined with the low inter row seed distance compared to corn visualize the challenge to implement a precise singulated metering for cereals.

Reducing the seed frequencies (seeds/sec) per seed opener can be a solution to implement a singulation system in cereals [76], an option could be narrower row spacings but this is technically feasible and economically not rentable. Lower driving speeds can be another option, but this will inevitably increase the cost of seeding operation as more working hours are needed or larger machine widths. Staying with winter wheat, potentials are given to reduce seed rates and thus reducing the seed frequency. Due to the plasticity of wheat, single plants can compensate growing space while maintaining the yield level down to 150 seeds/m² [54, 100]. Given by the above listed example of 300 seeds/m², the 50 % seed rate reduction could be a feasible opportunity reduce the seed frequencies by 50 %.

As it is known that winter wheat can still produce stable yields at seed rates below 150 seeds/m², it is worthwhile to further evaluate if an improved plant spacing quality can stabilize the yield production to much lower seed rates or if the yield increase can be further improved. This could also support the development of a potential singulation planter for the use in cereals, as the seed frequencies can be reduced while maintaining or increasing the wheat yield production.

2.5 Evaluation methods of longitudinal seed spacing quality

The distribution quality of seeds and finally plants in field effect the crop growth performance. It is mentioned to be agronomic beneficial for plant growth when the single plants are spaced equal and uniform across the area. In this way, every single plant will have the same individual growing space with reduced intraspecific competition, resulting in a more homogenous crop growth [29]. Because of this, the longitudinal seed distribution of seeders needs to be as uniform as possible [28]. Depending on the used seed metering, different seed spacing qualities can be achieved in field. To describe and compare the longitudinal seed spacing quality, specific statistical measurements and calculations are used to verify the seed distribution performance of seeding equipment.

For volumetric drill seeding, the number of plants in defined lengths along the trench are used for analysis. In contrary, when analyzing the seed spacing quality of singulation planters, the plant-to-plant distances are used. These two different ways of measurements are standardized test methods and specified by the International Organization for Standardization and can be find in “ISO 7256-1 for single seed drills (precision drills)” and “ISO 7256-2 for seed drills for sowing in lines” [45, 46]. Both methods describe the seed spacing of within-row spacing in a one dimensional way [33] and generate insights of the relative spacing accuracy, but specific insights of growth space area are missing [12]. Therefore, additional insight generation can be realized when analyzing potential plant growth spaces with Voronoi polygons (chapter 2.5.3).

2.5.1 Evaluating seed spacing quality for volumetric seed drills

The ISO 7256-2 specifies a standardized test method for volumetric seed drills in order to evaluate the longitudinal spacing quality in trench [46]. As seed spacing data of volumetric seed drills follow an exponential function when transferring into a histogram, no dispersion parameters are available to describe the probability function similar to a normal distribution. It is specified in ISO 7256-2 to sequence the seed rows in specified distances of 10 cm, followed by counting the number of seeds or plants within the sequences. These data can be visualized in a Poisson distributed histogram, describing the ratio of counting’s per sequence [10, 28, 78]. Besides the visualization, the coefficient of variation (CoV) is mentioned in ISO 7256-2 as parameter to describe the dispersion index of these data. Generally, the CoV is a meaningful value to describe the dispersion of data. As the generated data sets are based on a Poisson distribution using defined sequences, the average number of seeds/plants highly depend on

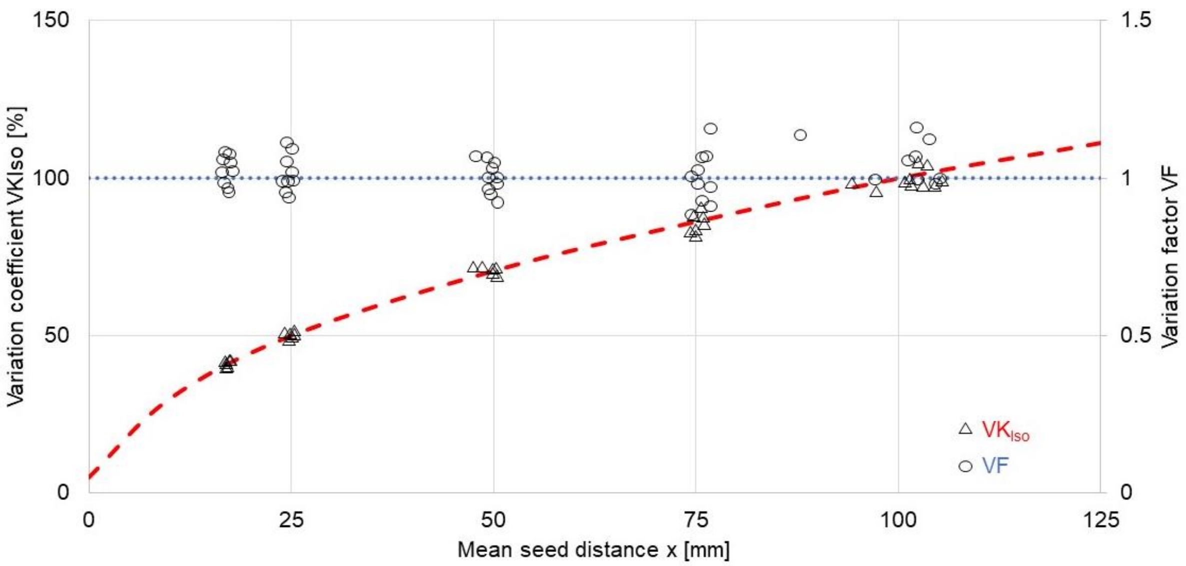

Figure 6: Variation coefficient VK_{ISO} according ISO 7256/2 and variation factor VF according DLG vs. seed spacing (Based on MÜLLER et al. (2001) [78]).

the used seed density. Hence, the CoV is systematically varying when seed rate is changed. Considering that seeders are tested with different seed rates, the CoV of sequenced plant counting's is not a suitable method to describe and compare the spacing accuracy [78]. Based on additional researches and recommendations, the variation factor (VF) (Equation 1) has been identified to deliver more reliable results to describe the dispersion index of the Poisson distributed values [28, 78]. Compared to using the CoV, the use of VF has more constancy when using different seed rates, indicated by the blue, small dotted line staying stable at a VF of 1 when target mean seed distance changes (Figure 6). In contrast, the red scattered line, reflecting the use of CoV for calculation, demonstrates increasing values when mean seed distance is enhanced and thus explaining the variation of the CoV. Besides using the VF, a reduction of seed counting sequences to 5 cm is also recommended as this is reducing the dispersion of the data and thus increasing the precision of the VF [28, 78]. The calculation of the VF is defined as following:

$$VF = \frac{Variance\ of\ sample}{Thoretical\ mean\ of\ Poisson}$$

Equation 1: Variation factor (VF) [28].

Referring to GRIEPENTROG (1991), the VF indicates the spacing accuracy as following:

VF > 1.1:	Compound Poisson, marked as over-disperse (high variation). A rare incident is followed by additional ones. Indication for high number of skips and multiples.
VF 0.9-1.1:	No excessive ratio of skips and multiples.
VF < 0.9:	Poisson is under-disperse (low variation). Reduced number of skips and multiples resulting in more uniform seed spacings [28].

Using the number of seeds in sequenced areas is stated to be a good compromise to evaluate the longitudinal seed distribution. The resolution is acceptable, and ratio of skips is reduced [28]. Nevertheless, it is not possible to quantify the distribution of seeds within the sequences [12, 28]. In addition, the ISO standardized test method is stated by MÜLLER et al. (2001) as not suitable to deliver satisfying results to describe the longitudinal spacing accuracy. Using the CoV of seed or plant distances is mentioned as alternative to increase the precision, based on a lower dispersion of the values [78]. Considering that seed spacings of volumetric drill seeders are characterized by the exponential function, mean and standard deviation, as used for CoV, are not recommended to be used to drive similar conclusions compared to normal distributed data. Nevertheless, the CoV of seed spacings of exponential functions can be used to determine the quality of seed spacing accuracy [77]

2.5.2 Evaluating seed spacing quality for singulation, precision seed drills

A standardized test method for evaluating the longitudinal spacing accuracy of singulation planters is defined in ISO 7256-1 [45]. When visualizing the plant spacings of singulation planters in a histogram, a normal distribution ranging around the theoretical seed spacing is characteristic (Figure 7). Besides this, several smaller peaks identify multiples and skips. The skips depend on the theoretical seed spacing, so several smaller peaks based on the theoretical seed spacing can be found. For this reason, KACHMAN & SMITH (1995) arranged the observed seed spacings by the deviation to theoretical seed spacing X. These classifications are also derived by the ISO 7256-1 and defined as following:

Multiple:	Seed spacings that are equal or less than the half of the theoretical seed spacing. X ≤ 0.5
Skip/miss:	Seed spacings that are greater than 1.5 times of the theoretical seed spacing. X > 1.5
Target range:	Seed spacings, that are more than a half but no more than 1,5 times of the theoretical seed spacing 0.5 < X < 1.5 [45, 49]

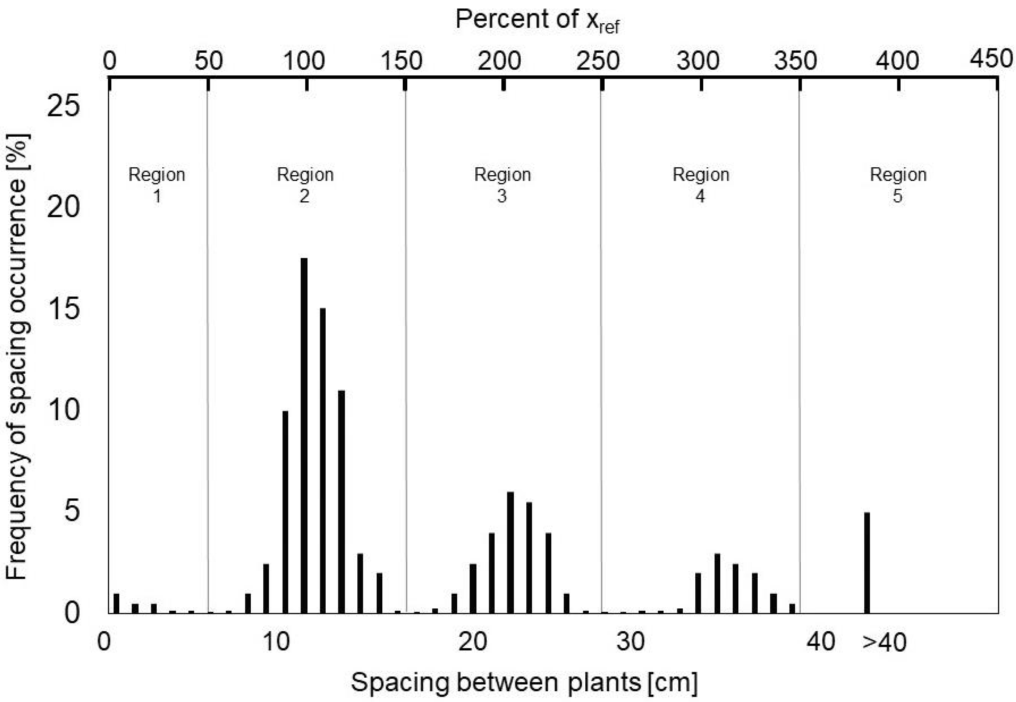

Figure 7: Estimation of multiples, missed/skipped seeds and target range of a precision planter (Based on KACHMAN & SMITH (1995) [49]).

The ratio of multiples, skips and seeds in target range can be expressed as percent to total values. To identify the variability of seed spacings, a precision index is calculated. This calculation reflects the coefficient of variation (CoV), using seed/plant distances in the target range:

$$C = \frac{S}{Xref}$$

S = *Standard deviation of observations in target range*

$Xref$ = *theoretical seed spacing*

Equation 2: Calculation of precision index (Based on KACHMAN & SMITH (1995) [45, 49]).

A lower CoV indicates a higher spacing accuracy. The CoV calculation based on the ISO is only reflecting the seed spacings ranging in area of target range. Outliers, including skips and multiples are not reflected within this calculation. Therefore, CoV's of 29 % and above indicate a large spread of the values within the target range and should be treated with care [49].

2.5.3 Two-dimensional crop space analysis: Voronoi polygons

When describing the longitudinal plant spacing accuracy along the trench using VF and/or CoV, the data represent the accuracy in a one-dimensional way [33]. On these facts, both methods do not consider the effects of different row spacings and seed rates while they effect the mean seed distance within the trench. Also, CoV and VF indicate only the quality of seed spacing but these values are not suitable to indicate the plant growth area and can't be used for additional statistical calculations or simulation processes [32]. Increased knowledge generation can be achieved when extending one-dimensional spacings into higher, two-dimensional settings [82], that deliver the opportunity to calculate potential plant growth spaces.

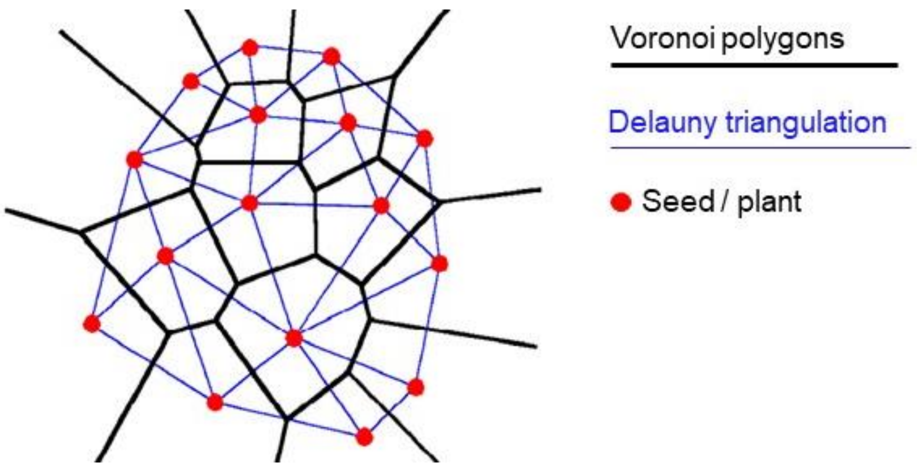

Figure 8: The construction of Thiessen or Voronoi polygons and Delauny triangulation (Based on GRIEPENTROG (1998) [31]).

The ideal growth space of an individual plant is a circular. When generating a uniform, equidistant seed pattern in field the individual growth space is characterized by a hexagon, which has the closest approximation to a circle [31, 72]. These so called Voronoi polygons have the highest similarities to the ideal plant growth space (Figure 8). Hence, the use of Voronoi polygons has been identified as adequate method to sequence the potential growing area of an individual plant within a population.

Voronoi polygons are a tessellation, using point coordinates as input in which each input is allocated a region of influence [67, 82]. Two procedures are known to identify the next neighboring point coordinates and thus the point specific surrounding area:

Delaunay triangulation:	Three points are neighbors when their common circle won't include another point
Voronoi polygons:	Points, that have a common boundary as result of a polygoning [30, 32, 82]

Both methods indicate the same three points as neighbors but only the Voronoi polygons deliver the opportunity of two-dimensional visualization of plant growth area [30, 32].

The use of Voronoi polygons is a useful tool for describing spatial statistics [82] and is an established method in Geo-Statistics to describe spatial distribution of data, for example weather. Additional use of Voronoi polygons has been successfully implemented in forestry systems to predict growth and yield potentials of trees. On this baseline, GRIEPENTROG (1995, 1998 & 1999) investigated research activities to describe the spatial distribution of canola plants with Voronoi polygons when using seeding techniques with different quality levels in longitudinal spacing [30–32]. The following parameters of the polygons are stated by GRIEPENTROG (1999) as useful parameters when quantifying the distribution quality of seed placement:

Polygon size:	Input for statistical analysis, comparing variation. E.g. CoV; visualization in Histograms.
Polygon shape:	Defined as shape-factor. Deviation of plant polygon shape to ideal formed polygon shape.
Eccentricity:	Position of point (plant) within polygon [32].

One more potential of Voronoi polygons is the use and implementation in plant growth simulation models. For example, agricultural field crops adapt plant growth depending on available growth space and thus competition to the next neighbor. When the growing space is getting lower the single plant yield production is reduced. As the single plant yield is not equivalent with the yield per area, a correct balance of plant density and according to single plant yield is needed to generate the maximum yield production per area. This can be visualized in yield potential curves.

When combining knowledge of individual plant growth space in field with the potential yield production, the specific yield response can be added to each polygon depending on its size. Based on GRIEPENTROG (1995 & 1998) evaluations using this method in canola, yield increases of 6 % when improving longitudinal seed spacing with a planter and 11 % when equidistant spaced can be predicted, compared to volumetric, random seed distribution [30, 31]. To increase the accuracy of yield prediction when using size of Voronoi polygons, the specific reaction of a yield curve, reflecting different crop types and varieties under different environmental and climate conditions, is needed. These insights can be supplementary input to drive upcoming crop management strategies and in particular fertilization and plant protection. Additionally this knowledge is stated to be valuable for defining the ideal spacing of the seeds to achieve maximum yield potential while reducing the population density to an agronomic optimum (Figure 9) [12].

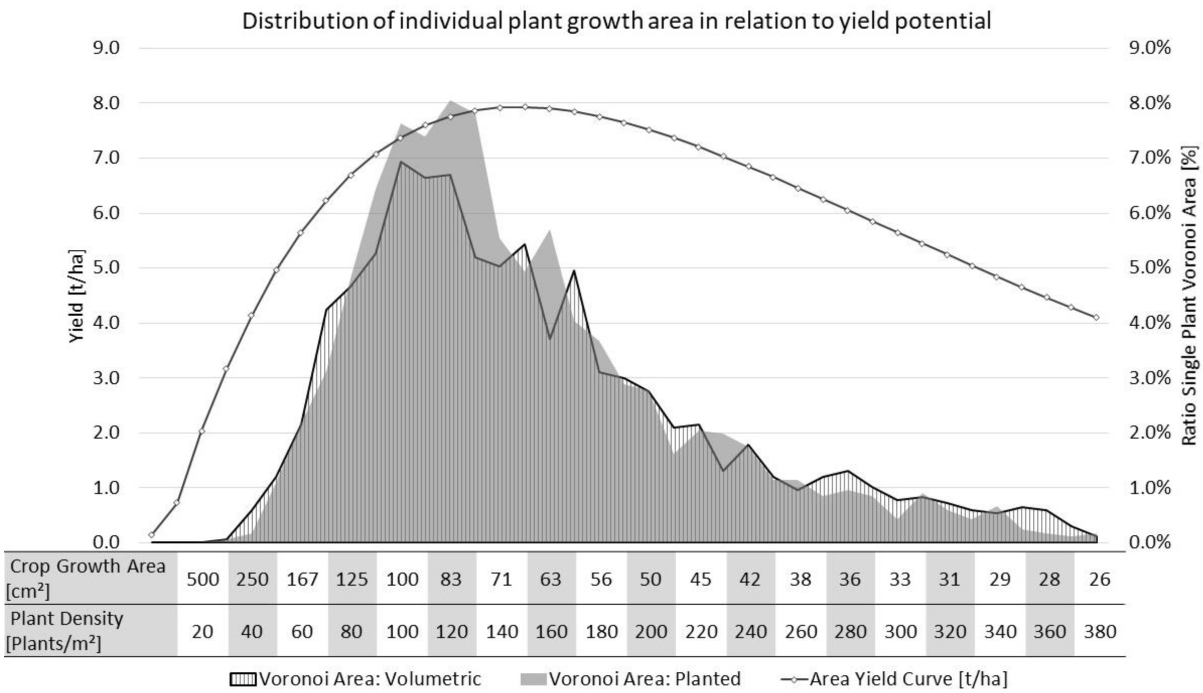

Figure 9: Winter wheat yield curve and voronoi plant distribution of volumetric and planted seeding (Based on BUND et al. (2020) [12]).

2.6 Economic aspects of seeding winter wheat

In relation to costs for fertilization and plant protection, seed costs of European farmers have low impact, ranging between 15-25 % of crop management costs. This reflects seed costs of 55-75 €/ha (Figure 10) [20].

Although it is possible to reduce seed densities by half while maintaining the yield, farmers won't apply seed rate reductions as the higher plant population density can be a low-cost

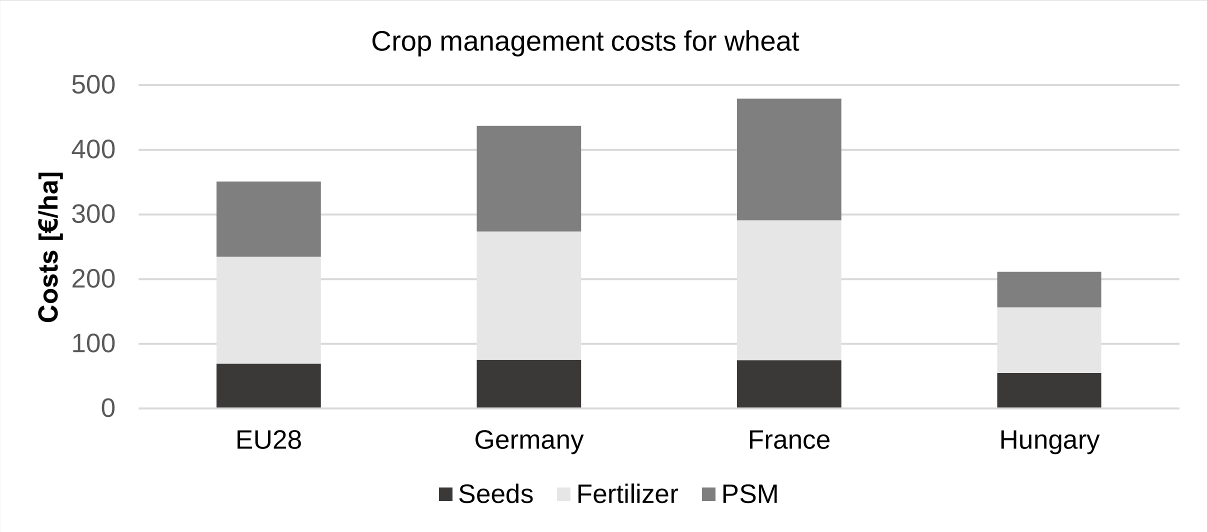

Figure 10: Average wheat crop management costs per hectare for seeds, fertilizer and plant protection in EU28, Germany, France and Hungary (Adapted from EU CEREAL FARMS REPORT (2019) [20]).

insurance if plant losses occur during winter or if the growing conditions in spring are not good enough to produce sufficient ear bearing stems per plant [91, 96]. Also, higher seed rates are connected with an improved weed suppression [33, 47]. As winter wheat is commonly seeded with volumetric seed drills, these points are eligible as low seed densities in combination with random seed distribution can cause inefficient usage of growing area [31, 33, 76].

Assuming that the use of a singulation planter distributes cereals in a comparable quality than corn or sugar beets, the costs of a potential singulation solution can be upscaled based on the row units used. The average machine costs per hectare of a volumetric seed drill and a singulation planter are in a similar range, but differing in the row units/seed openers as listed:

Volumetric seed drill (3 m work width, 20-24 seed openers): 27.50 – 34.00 €/ha*

Singulation planter (2.7/4.5 m work width, 6 row units): 28.00 – 35.00 €/ha*

*machine costs derived from cost matrix for agricultural machinery [57, 69]

Imagine a technical concept, using singulation row units at comparable narrow row spacings as used in cereals, 3-4 times higher costs can be estimated when upscaling from a 6-row planter to a 20-24 row unit planter. This results in minimum 66 €/ha higher costs for seed machinery. These costs need to be compensated by the stated advantages when singulating wheat seeds, that declare seed cost savings and higher yields.

However, this value is roughly estimated as no potential solution for singulating cereals is adapted on market yet for reference [53]. Because of that it is still necessary to define the monetary value when wheat is singulated, as this value can be used as parameter for new technical developments that are able to improve the plant space quality in field.

3. Material and methods

In cooperation with the John Deere GmbH & Co. Kg., a field trial was conducted beginning October 2018 till August 2020 to verify the agronomic and economic potentials when improving the longitudinal seed spacing accuracy in winter wheat. The research included the comparison of two different seed metering systems at four seed rates and two winter wheat varieties. To proof the constancy of the results under varying conditions, the field trial was executed for two growing seasons at two different locations in Germany. Additional field trial execution was executed in the second field trial year in France and Hungary to reflect the agronomic behavior at different environments and yield potential zones.

3.1 Test factors

3.1.1 Seeding technique

Two seeder types with different kind of seed metering were tested to compare the quality of longitudinal seed spacing accuracy and its effects on crop growth and yield production.

(1) **VS** – Volumetric seeding: John Deere 750A

The John Deere 750A is equipped with a central, volumetric seed dosage. After seed metering, the seeds are distributed via air stream to the seed openers, resulting in a random seed distribution. As this kind of seed dosage is typically used when seeding small grains like wheat, this seeder represented the commonly used farming practice. The row spacing was 16.67 cm.

Figure 11: Volumetric seeder for field test execution: John Deere 750A.

(2) **SP** – Singulation planter

Seeding 2018: John Deere ExactEmerge

An ExactEmerge singulation planter was used as reference for improved seed spacing quality in trench. After singulating the seeds within the metering unit, seeds were actively transported by a turning brushbelt into the trench. Due to a wide row spacing of 37.5 cm, the plots were seeded a second time after shifting the GPS-Line by 18.75 cm.

The ExactEmerge planter was replaced in the second year of field trial execution due to technical issues.

Figure 12: Singulation planter for field test execution: John Deere ExactEmerge. Left: Machine for field trial seeding. Right: Single row unit

Seeding 2019: Monosem Monoshox NG Plus M

The Monosem singulation planter was used in 2019 as replacement for the ExactEmerge planter. At the Monosem, seeds were singulated and then falling through the seed tube into the trench. The row spacing was set to 33 cm. Just like with the ExactEmerge, the plots were seeded twice after shifting the GPS-Line by 16.5 cm. Because of limitations in single seed output when using the singulation planter, the operating speed while seeding in field was set to 4 km/h.

Figure 13: Singulation planter for field test execution: Monosem NG Plus M. Left: Machine for field trial seeding. Right: Singulation disc equipped with grains

3.1.2 Winter wheat varieties and seed density

Two different winter wheat varieties, a non-hybrid variety (NH) and a hybrid variety (HY), were tested in field. Based on the variety specific characteristics, both wheat varieties are mostly comparable to each other (Table A 1).

(1) RGT Reform (Non-hybrid wheat variety) - **NH**
(2) SU Hymalaya (Hybrid wheat variety) - **HY**

Both wheat varieties were tested at four seed rates:

(1) 80 seeds/m² - (14.67 seeds/sec*)
(2) 160 seeds/m² - (29.33 seeds/sec*)
(3) 240 seeds/m² - (44.00 seeds/sec*)
(4) 320 seeds/m² - (58.67 seeds/sec*)

*at 4 km/h operating speed

3.2 Field trial locations

The field trials were set up at different test sites across Europe to reflect the agronomic potentials under varying climate and environmental conditions (Table 1). The German test sites in Rauischholzhausen (University Giessen) and Oschersleben were tested in two growing seasons (2018/2019 and 2019/2020), the test sites in Hungary and France one time in the growing season 2019/2020.

The application of fertilizer and crop protection during crop growth was done customarily. Variations were only given between the individual Test Sites and years to adapt on the specific growing conditions, reflecting the emphasis of good agricultural practice.

Growing season 2018/2019

Germany: University Giessen, Test Site Rauischholzhausen (**Test Site GI19**)
Germany: Oschersleben, Bode (**Test Site OS19**)

Growing season 2019/2020

Germany: University Giessen, Test Site Rauischholzhausen (**Test Site GI20**)
Germany: Oschersleben (Bode) (**Test Site OS20**)
France: Romilly-La-Puthenaye (**Test Site FR20**)
Hungary: Végégyhaza (**Test Site HU20**)

Table 1: Characteristics of the Test Sites for field trial execution.

	Germany	Germany	Hungary	France
	Oschersleben (Bode)	**University Giessen, Test Site Rauischholzhausen**	**Végégyhaza**	**Romilly-La-Puthenaye**
above N.N.	85 m	235 m	93 m	155 m
Climate zone	Continental climate	Continental climate	Pannonian climate	Oceanic climate
Avg. temperature	9.9 °C	8.6 °C	10.5 °C	9.8 °C
Avg. rain fall	542 l/m²	616 l/m²	495 l/m²	785 l/m²
Soil	Chernozem (Silty loam)	Luvisol (Clayey silt)	Chernozem (Silty loam)	Cambisol (Clayey loam)
Winter wheat Yield potential	7-8 t/ha	10 t/ha	5-6 t/ha	11-12 t/ha

3.2.1 University Giessen: Test Site Rauischholzhausen

At the Test Site of the University in Giessen, the main crop growth period for winter wheat ranged from October to July. During this period, rain fall events were exceeding the long-term

Table 2: Monthly average air temperature (T air) and monthly precipitation (Precip) during growing season 2018/2019, 2019/2020 and long-term average at University Giessen, Test Site Rauischholzhausen. x = not measured.

	2018/2019		2019/2020		Long-term average (1953-2020)	
Month	T Air [°C]	Precip [mm]	T Air [°C]	Precip [mm]	T Air [°C]	Precip [mm]
October	10.3	14	9.9	18	8.8	50
November	5.2	33	5.0	57	4.1	47
December	3.9	105	3.1	66	1.0	51
January	0.8	36	3.2	59	0.0	42
February	3.5	30	5.5	130	0.3	41
March	6.7	93	5.8	72	4.1	38
April	9.5	43	10.1	20	8.2	40
May	11.0	111	11.8	25	13.0	58
June	19.0	58	16.4	100	15.8	65
July	18.7	59	17.7	26	16.9	64
August	18.25	9.8	22.9	7	17.0	74
September	x	x	x	x	13.3	46
Year	8.9	582	10.1	580	8.6	616

average within both test years, but with differing rain distribution. In GI19, more than double the amount of rain compared to long term average was measured in December, March and May while the other months followed the long-term average. In contrary, GI20 had excessive higher amounts of rain from November to March, followed by a drier period with more than 50 % less rain in April, May and July. All in all, the rain fall distribution was good enough in both years to fill up soil resources that compensated drier periods in spring.
The average temperature was warmer for both test years. Especially the wintertime from December to March was warmer compared to long term average, with trend of higher temperatures in GI20. In GI19, extremely higher temperatures up to 37 °C within the second half of June increased the temperatures above the long-term average.

3.2.2 Oschersleben (Bode)

The main growth period for winter wheat is in Oschersleben between October to beginning of July. During both test years, less rain was measured compared to long term average. The test year OS19 was also characterized by dry summer period before seeding resulting in no available soil water while seeding. Below average rainfalls in October, November and February could not be fully compensated by the above average rain falls in December, January and March. While OS19 had in total 57 l/m² less rain, 19 l/m² less were measured in OS20. The

Table 3: Monthly average air temperature (T air) and monthly precipitation (Precip) during growing season 2018/2019, 2019/2020 and long-term average in Oschersleben (Bode). x = not measured.

	2018/2019		2019/2020		Long-term average (1991-2020)	
Month	T Air [°C]	Precip [mm]	T Air [°C]	Precip [mm]	T Air [°C]	Precip [mm]
October	9.1	6	12.2	24	10.0	39
November	5.3	11	5.5	37	5.6	41
December	4.7	59	4.0	46	2.6	41
January	1.5	59	4.1	23	1.5	39
February	4.9	9	6.1	82	2.1	30
March	7.2	73	5.1	28	5.1	38
April	9.8	31	9.3	2	9.5	32
May	11.7	37	11.5	20	13.6	56
June	20.9	71	17.5	112	16.8	58
July	17.6	29	17.6	46	19.0	66
August	x	x	22.0	18	18.7	57
September	x	x	x	x	14.5	45
Year	9.3	385	10.4	438	9.9	542

rainfall distribution followed nearly the long-term average till march, with enhanced rain fall in February. Interestingly, no rain was measured in April and 65 % less in May, followed by intense rainfall events end of May and beginning of June.

In average, higher temperatures during growing period were measured for both test years. The winter tended to be cooler in OS19, therefor much higher temperatures up to 38 °C maximum were detected in the second half of June. In OS20, warmer temperatures were measured from December to March, while the average temperature followed the long-term average from March to July.

3.2.3 Végégyhaza (Hungary)

As the Pannonian climate in Hungary is characterized by low rain falls, cold winters and warmer spring and summer temperatures, the main growing period of winter wheat ranges between October to mid of June. Right before and after seeding, untypical warm and dry conditions depleted the soil water storage. Compared to long-term average, 50 l/m² less rain was measured from November to May, indicating dry growing conditions with 206 l/m² in total during this period. In June, intense rain falls delivered the triple amount of rain that compensated the lower rainfall of the previous months. Much warmer temperatures after seeding and during winter were measured in Hungary compared to long-term average. In November, December

Table 4: Monthly average air temperature (T air) and monthly precipitation (Precip) during growing season 2019/2020 and long-term average in Végégyhaza (Hungary). x = not measured.

	2019/2020		Long-term average (1961-1990)	
Month	T Air [°C]	Precip [mm]	T Air [°C]	Precip [mm]
October	x	x	11.0	26
November	10.0	38	5.1	41
December	3.8	24	0.6	40
January	-1.2	12	-1.8	29
February	5.2	45	0.9	25
March	7.3	49	5.6	29
April	12.2	8	11.1	41
May	15.5	30	16.2	51
June	20.7	199	19.2	72
July	22.0	11	20.8	50
August	x	x	20.2	57
September	x	x	16.5	34
Year	10.6	417	10.5	495

and February 3-5 °C warmer temperatures were measured in average. In spring, the average temperatures followed mostly the long-term average with a trend of increased temperatures in June and July.

3.2.4 Romilly-La-Puthenaye (France)

The French Test Site located in the Normandie is charactered by Oceanic climate. Sufficient rain falls and mild temperatures during crop vegetation deliver potential for a high winter wheat yielding environment. Main crop growth period for wheat is between October to mid of July. Before and after seeding, above average rainfall events were measured, resulting in 106 l/m² more water compared to long-term average in the period of November-March. During the further crop development from April to July, more than 50 % less rain was measured, resulting in a drier season in spring.

Also, above average temperatures were measured during crop growth period. Besides a warmer winter, much warmer spring temperatures were measured compared to long-term average.

Table 5: Monthly average air temperature (T air) and monthly precipitation (Precip) during growing season 2019/2020 and long-term average in Romilly-La-Puthenaye (France). x = not measured.

	2019/2020		Long-term average (1969-1990)	
Month	T Air [°C]	Precip [mm]	T Air [°C]	Precip [mm]
October	8.8	4	10.9	67
November	7.1	118	6.4	83
December	6.0	106	4.1	76
January	5.8	31	3.3	71
February	7.7	150	3.6	59
March	7.0	59	5.9	69
April	11.8	29	8.2	50
May	13.0	26	12.0	72
June	18.7	35	14.8	59
July	18.7	21	17.1	60
August	x	x	17.0	54
September	x	x	14.5	65
Year	10.5	578	9.8	785

3.3 Field test design

The research factors were implemented in the same field trial design in both years and at all test sites. A split-split plot design has been chosen, grouping the factor variety in the first sub-plot and factor technique as sub-sub-plot, followed by a randomized distribution of factor seed rate within the sub-sub-plots. Four repetitions were executed in Giessen/Rauischholzhausen and Oschersleben, three repetitions in France and Hungary. The plot size was 3x10 meter in Giessen/Rauischholzhausen, France and Hungary.

In Oschersleben, a large scaled field trial having 9x135 meter plot size was created. Due to the larger field trial dimension, an increased heterogeneity in field was expected. To ensure an equal plot randomization, an extrapolated field map was created upfront, using soil texture mapping and yield maps. The identification of field heterogeneity has been used to distribute the four repetitive blocks into equal field zones.

3.4 Field data evaluation

3.4.1 Plant space distribution quality

As two different types of seed metering systems were used, the quality of longitudinal seed distribution was evaluated, using the plant distances after field emergence. Therefore, the distances of 20 plants in row were measured, selecting two sections for measurement in Giessen/Rauischholzhausen and France, three in Oschersleben and ten in Hungary. To compare the variability of seed spacings, the coefficient of variation (CoV) was calculated as statistical parameter for data comparison. For each measuring area, a CoV was separately calculated.

$$CoV = \frac{s}{Xref} = \frac{standard\ deviation}{Thoretical\ seed\ spacing}$$

Equation 3: Coefficient of variation.

The CoV is a well-known statistical value to describe dispersion of values. Also, the use of CoV is listed in ISO 7256-1 as value to compare the quality of seed spacing performance. While ISO 7256-1 is using for calculation only values within target range, excluding skips and multiples [45], all plant spacings were reflected for CoV calculation in this research.

3.4.2 Plant density, tillering and ear density

During the growing period, plant density, tiller and ear formation were evaluated in field. Therefore, sections of one meter seed row were randomly selected in the plot and marked with sticks. In Giessen/Rauischholzhausen and France, two counting sections per plot were marked and three in Oschersleben. In Hungary, three counting areas were marked. In contrary to the other Test Sites, ten neighboring seed rows of one meter were counted and separately documented in Hungary.

The number of plants was counted within the one-meter sections and values were calculated afterwards up to one square meter, using the by seed technique given row spacing:

$$x = N * \left(\frac{100}{Row\ spacing\ (cm)}\right)$$

N = counts in 1 m section (Plants, tillers, ears)

x = Individuals per square meter

Equation 4: Calculation of plant / tiller / ear density per m² using counts per meter and row spacing.

The same procedure was used to evaluate the density of tillers and ears. Due to marking the counting areas upfront, tiller and ear counting was done in the same section than plant counting. Using this approach, the potential of single plants to produce tillers and ears was calculated by dividing tiller or ear density by plant density. As the same counting areas were used, increased accuracy of this calculation can be assumed.

In first field trial season, a second counting of plant density was done after winter to evaluate plant losses. Because of a warmer winter period in the second year of field trial execution, larger grown plants after winter made it impossible to distinguish between plants and tillers. For additional calculations of the second year, the evaluated field emergence in autumn was used, assuming no winter losses.

In spring 2020, restrictions in travelling due to COVID caused limitations in evaluating the tiller formation. For this reason, tillering was only evaluated in GI19, OS19 and GI20.

3.4.3 Grain yield and grain quality parameters

The yield data of GI19, GI20, FR20 and HU20 were evaluated with a plot combine and 1.50 m working width, combining and measuring the grain weight only of the middle core plot section. While in GI19, GI20, OS19 and FR20 just one yield measurement per plot was evaluated, four yield measurements per plot were evaluated in HU20.

The yield measurement at the larger scaled field trial in Oschersleben was done differently between both test years. In the first test year, a John Deere T670i combine, equipped with a 7.60 m header was used to combine the inner core of the 9 m wide plots at a length of 135 m. For weight measurement, each plot was unloaded separately into a container, staying on a platform scale.

A plot combine was used in the second test year in Oschersleben to increase the number of yield sampling data. Equipped with distance tracking and GPS, 10-12 randomly chosen spots for yield measurement in each plot were used for data generation.

After yield data sampling at all locations, the values were calculated to weight per hectare:

$$Yield\ [t/ha] = \frac{Wplot}{Aplot} * 10$$

Wplot = Weight per plot [kg]

Aplot = Area per plot [m²]

Equation 5: Calculation of yield samples to yield per hectare [t/ha].

During harvest, grain samples were taken from each harvested spot. Using a NIRS-Spectrometer, the grain samples were analyzed for grain moisture and protein content. In addition, grain weight (TKW - thousand kernel weight) was evaluated.
Grain moisture was used to recalculate yield data onto an equal grain moisture of 14 %:

$$Dry\ Yield\ [14\ \%\ moisture) = Yield * \frac{100 - Grain\ moisture\ [\%]}{100-14}$$

Equation 6: Recalculation of grain weight to an equal grain moisture of 14 %.

The average number of grains per ear was calculated also, using harvested grain yield, grain weight and the number of ears/m² as reference:

$$Grain\ number\ per\ ear = \frac{Yield\ [t/ha]}{Ear\ density * TKW} * 100.000$$

Equation 7: Calculation of grain number per ear.

3.5 Statistic analysis

For statistical analysis, the software R-Studio (Version 1.4.1717) was used. The field trial factors were analyzed using a linear mixed-effect model (lmer) to reflect the mixed and random model effects of the split-split-plot design. Factor variety has been used as first sub-plot, factor technique as sub-sub-plot. The main plots were filled by factor seed rate. As variety and technique acts as sub plots, their random effects were recognized as well. The different Test Sites were handled as fixed effects. As the number of the specific evaluated data sets varied between the Test Sites, the average number per individual plot was calculated upfront and used for further analysis.

*Y = Variety * Technique * Seed rate * Test Site * (1|Block) * (1|Block:Variety) * (1|Block:Variety:Technique)*

Equation 8: Model baseline for ANOVA and Post-Hoc analysis of field trial data [94].

Using this model as baseline, an ANOVA analysis, reflecting "Kenward roger step 1" approximation, was executed upfront to indicate potential significant impact of the test factors and their interactions. While the following result section shows the summary of the F- and p-values, the detailed ANOVA results of the individual evaluated parameters are listed in the appendix (Table A 2-13).

In a next step, the identified significant factors and interactions were analyzed by using a Post-Hoc analysis (EMMEANS) to identify the significances of the individual factor levels and its interactions. As reference, the Tukey-method was used at a predefined alpha error of 0.05.

Also, a linear regression analysis was used in specific cases to define the independent variables that explain the impact on the dependent variable. Therefore, the linear model function (lm) of RStudio was used to define the regression parameters of the chosen variables and its interactions.

3.6 Yield regression modeling

Defining yield data as dependent variable in a linear squared regression model, yield functions were estimated using the independent factors technique, variety, seed rate and its interactions as explaining variables. As yield growth is decreasing with marginal return when increasing the seed rates, seed rate was also included as squared variable:

$$\textit{Yield} = \textit{Variety} * \textit{Technique} * \textit{Seed rate} + (\textit{Seed rate})^2$$

Equation 9: Linear squared regression model for estimating the agronomic yield curve.

Using this term, each Test Site was analyzed individually. For generating an average regression term for all Test Sites, the factor Test Site was used as Dummy Variable.

$$\textit{Yield} = \textit{Variety} * \textit{Technique} * \textit{Seed rate} + (\textit{Seed rate})^2 + \textit{Test Site}$$

Equation 10: Linear squared regression model for estimating the agronomic yield curve including Test Site as dummy variable.

After calculating the estimates of the individual Test Sites, factors and its Interactions, the agronomic yield curve of the combinations technique and variety in terms of seed rate was created. Using these curves, specific points of interest were analyzed:

1. **Agronomic optimum seed rate:**
   Maximum yield production [t/ha] and corresponding seed rate
2. **Seed rate - Yield threshold technique:**
   Curve intersection technique volumetric seeding and singulation planter
3. **Potential seed rate reduction of technique singulation planter:**
   Maintaining maximum yield [t/ha] of technique volumetric seeding

Using the agronomic yield curve data as baseline, the economic curve was calculated also, reflecting market price of wheat and the price of the seed costs. These values are defined as gross margin:

Market price wheat: 180 €/t *(Price based on average wheat price in 2020)*

Seed costs: *(Price per hectare)*
Non-hybrid: 0.20 €/10,000 seeds per hectare
Hybrid: 1.32 €/10,000 seeds per hectare

*Euro/ha = Yield [t/ha] * Market price – Seeds/m² * Seed costs*

Equation 11: Calculation of economic yield curve, reflecting gross margin.

Likewise the analysis of the agronomic yield curve, the points of interest were analyzed also to specify the economic thresholds:

1. **Economic optimum seed rate:**
   Maximum gross margin [€/ha] and corresponding seed rate
2. **Seed rate – gross margin threshold technique:**
   Curve intersection technique seeding and singulation planter
3. **Potential seed rate reduction technique singulation planter:**
   Maintaining maximum gross margin [€/ha] of technique volumetric seeding

To ensure the confidentiality of the estimated results for agronomic and economic optimum seed rate, a maximum range for value generation of 50-400 seeds/m² was set. Generated values that exceed or fall below this threshold were replaced with the maximum or minimum threshold of the set range.

4. Results

4.1 Crop establishment

After wheat seed emergence in autumn, the evaluation of plant density and thus emergence rate, CoV calculations of plant-to-plant distances and an evaluation of plant losses after winter were used to verify the crop establishment in field. In contrast to emergence rate and CoV, winter losses were only evaluated within the first field trial season in GI19 and OS19. Due to a sophisticated plant development rate in the second year of field trial execution, it was not possible to evaluate the plant density for a second time after winter. Nevertheless, the ANOVA analysis indicated significant impact of the tested factors and interactions for those three parameters (Table 6).

Table 6: Effects of technique (Tec), seed rate (SR), variety (V) and Test Site (TS) on winter wheat seed emergence, coefficient of variation (CoV) of wheat plant distances and winter losses of wheat plants.

		Seed emergence		**Plant distances: Coefficient of variation**			**Winter losses**	
Factors	NumDF	F value	Pr(>F)	F value	Pr(>F)	NumDF	F value	Pr(>F)
Tec	1	17.390	0.007 **	242.305	< 0.001 ***	1	2.356	0.180
SR	3	79.872	< 0.001 ***	8.743	< 0.001 ***	3	14.216	< 0.001 ***
V	1	35.672	0.012 *	0.092	0.783	1	0.381	0.584
Tec x SR	3	3.438	0.018 *	8.544	< 0.001 ***	3	0.372	0.774
Tec x V	1	0.011	0.919	0.850	0.395	1	0.936	0.374
SR x V	3	0.155	0.926	0.452	0.716	3	0.767	0.515
Tec x SR x V	3	1.938	0.124	0.945	0.419	3	1.518	0.214
TS	5	66.433	< 0.001 ***	12.783	< 0.001 ***	2	30.929	< 0.001 ***
Tec x TS	5	36.377	< 0.001 ***	3.697	0.003 **	2	0.424	0.655
SR x TS	15	5.048	< 0.001 ***	2.827	< 0.001 ***	6	1.878	0.090 .
V x TS	5	6.980	< 0.001 ***	1.147	0.336	2	0.078	0.925
Tec x SR x TS	15	4.148	< 0.001 ***	0.517	0.930	6	0.450	0.844
Tec x V x TS	5	3.311	0.007 **	0.569	0.724	2	0.125	0.883
SR x V x TS	15	1.085	0.370	0.558	0.904	6	0.214	0.972
Tec x SR x V x TS	15	1.662	0.059 .	0.831	0.642	6	0.174	0.983

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

4.1.1 Emergence rate

While the ANOVA declares significant impact on emergence rate for most tested factors and their interactions (Table 6), a clear trend on impacting crop emergence was observed for seed rate, variety and Test Site (Table 7). Increasing the seed rate results in a significant reduction of the emergence rate. In total average, nearly all seeds emerged at the lowest seed rate while the highest seed rate resulted with an emergence factor of 74.1 %.

Table 7: Average winter wheat seed emergence of the Test Sites for technique, variety and seed rate. Values followed by a different letter are significantly different within columns and for mean of Test Sites within row ($p < 0.05$).

	Emergence rates of Test Sites						
	GI19	OS19	GI20	OS20	HU20	FR20	**Mean**
Technique							
VS	96.8% B	91.1% B	107.9% B	99.1% B	68.5% A	49.6% A	85.5% A
SP	81.9% A	74.1% A	92.6% A	85.5% A	84.9% B	76.6% B	82.6% A
Variety							
HY	88.7% A	83.1% A	94.6% A	89.5% A	65.6% A	58.5% A	80.0% A
NH	89.9% A	82.1% A	105.9% B	95.0% A	87.8% B	67.7% B	88.1% B
Seeds/m²							
80	111.8% C	102.2% B	113.3% B	97.7% B	85.1% B	76.2% B	97.7% C
160	96.9% B	92.6% B	97.5% A	91.8% AB	78.2% AB	65.2% AB	87.1% B
240	77.6% A	67.8% A	97.9% A	92.6% AB	72.4% AB	55.5% A	77.3% A
320	70.9% A	67.8% A	92.2% A	87.1% A	71.0% A	55.4% A	74.1% A
Mean	89.3% C	82.6% B	100.0% D	92.3% C	76.7% B	63.1% A	

Having a specific view at the Test Sites, differing ranges in crop emergence can be seen. In test year 2019, the emergence ranged in GI19 with a difference of 40.9 % and in OS19 with 34.4 % between lowest and highest seed rate. In contrary, the range was reduced in the second test year to 21.1 % in GI20 and 10.6 % in OS20. A similar response can be seen with a range of 14.1 % in HU20 and 20.4 % in FR20 under consideration that the emergence rate was in general lower compared to the Test Sites GI19, GI20, OS19 and OS20. This explains on the one side the significant difference in plant emergence between the Test Sites and the significant interaction of seed rate and Test Sites on the other side (Table 6). Comparing the varieties to each other, a significant higher emergence rate was indicated for non-hybrid wheat with 8.1 % more compared to hybrid wheat. This effect is interacting with the tested locations and mainly differing in GI20, HU20 and FR20.

In average, the factor technique has low significant impact but gets increased importance when interacting with Test Site. In both test years of Giessen and Oschersleben the volumetric seeding has a significant higher emergence rate compared to the singulation planter. An inverse reaction can be seen in HU20 and FR20, here the singulation planter produces a significant higher plant emergence.

4.1.2 Plant losses over winter

Plant losses over winter were only evaluated in GI19 and OS19. However, seed rate and Test Site are significantly differing with low interaction to each other (Table 6). At both Test Sites the number of plant losses during winter is increasing when seed densities are getting higher (Figure 14). While the plant losses in OS19 ranged from zero at the lowest seed rate up to 40 plants/m² lost at the highest seed rate, GI19 had a significant higher range from 11 plants/m² lost at the lowest rate up to 54 plants/m² lost at the highest seed rate.
No significant impact on plant losses over winter was detected between the tested winter wheat varieties and used seeding techniques.

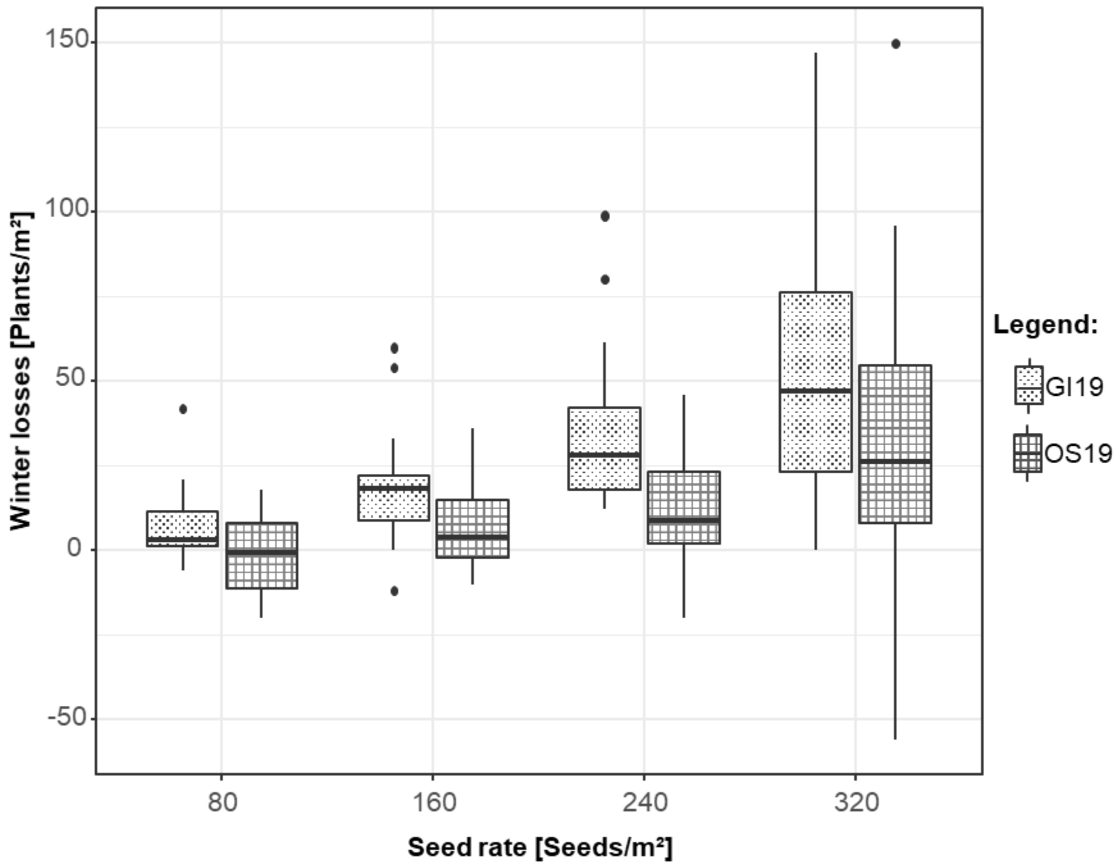

Figure 14: Winter losses of winter wheat plants of the Test Sites (GI19, OS19) depending on seed rate, merged over variety and technique.

When combining the increased number of plant losses with the emergence rate, the plant density of 320 seeds/m² differs with 45 % less plants compared to targeted seed rate

(Figure 15). This gap is reduced at lower seed densities, having 13 % deviation of seed rate to plant density at 160 seeds/m². Only the density of 80 seeds/m² stays mainly unaffected when comparing seed rate with plant density after winter.

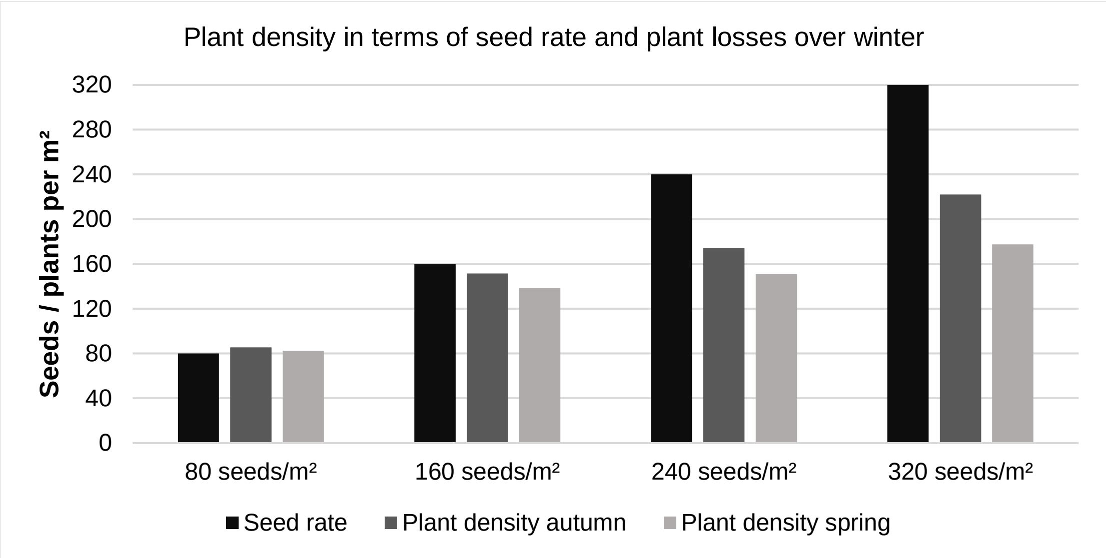

Figure 15: Deviation of seed rate to average plant density after seed emergence in autumn and after reflecting plant losses over winter, merged over Test Site (GI19, OS19), variety and technique.

4.1.3 Variation of plant-to-plant distances

As indicator for the plant-to-plant distances along the trench the coefficient of variation (CoV) was used to compare the quality of longitudinal plant spacing accuracy. Referring to the results of the ANOVA, technique, seed rate and their interaction significantly impact the CoV (Table 6). On average the CoV of the singulation planter is 27 % lower compared to

Table 8: Average coefficient of variation (CoV) of winter wheat plant spacings for factor technique depending on seed rate, merged over variety and Test Site (GI19, OS19, GI20, OS20, FR20, HU20). Values followed by a different letter are significantly different within columns and rows and for mean in row ($p < 0.05$).

	CoV of plant spacings	
	Volumetric seeding	Singulation planter
Seeds/m²		
80	90% ^{D}	51% ^{A}
160	92% ^{D}	62% ^{AB}
240	91% ^{D}	69% ^{BC}
320	89% ^{D}	73% ^{C}
Mean	91% ^{B}	64% ^{A}

Table 9: Average coefficient of variation (CoV) of winter wheat plant spacings for factor technique depending on Test Site, merged over variety and seed rate. Values followed by a different letter are significantly different within rows for technique and within column for mean ($p < 0.05$).

	CoV of plant spacings		
	Volumetric seeding	Singulation planter	**Mean**
Test Site and year			
GI19	73% ^{B}	60% ^{A}	67% ^{A}
OS19	99% ^{B}	67% ^{A}	83% ^{B}
GI20	94% ^{B}	63% ^{A}	79% ^{B}
OS20	102% ^{B}	68% ^{A}	85% ^{B}
HU20	82% ^{B}	55% ^{A}	69% ^{A}
FR20	93% ^{B}	69% ^{A}	81% ^{B}

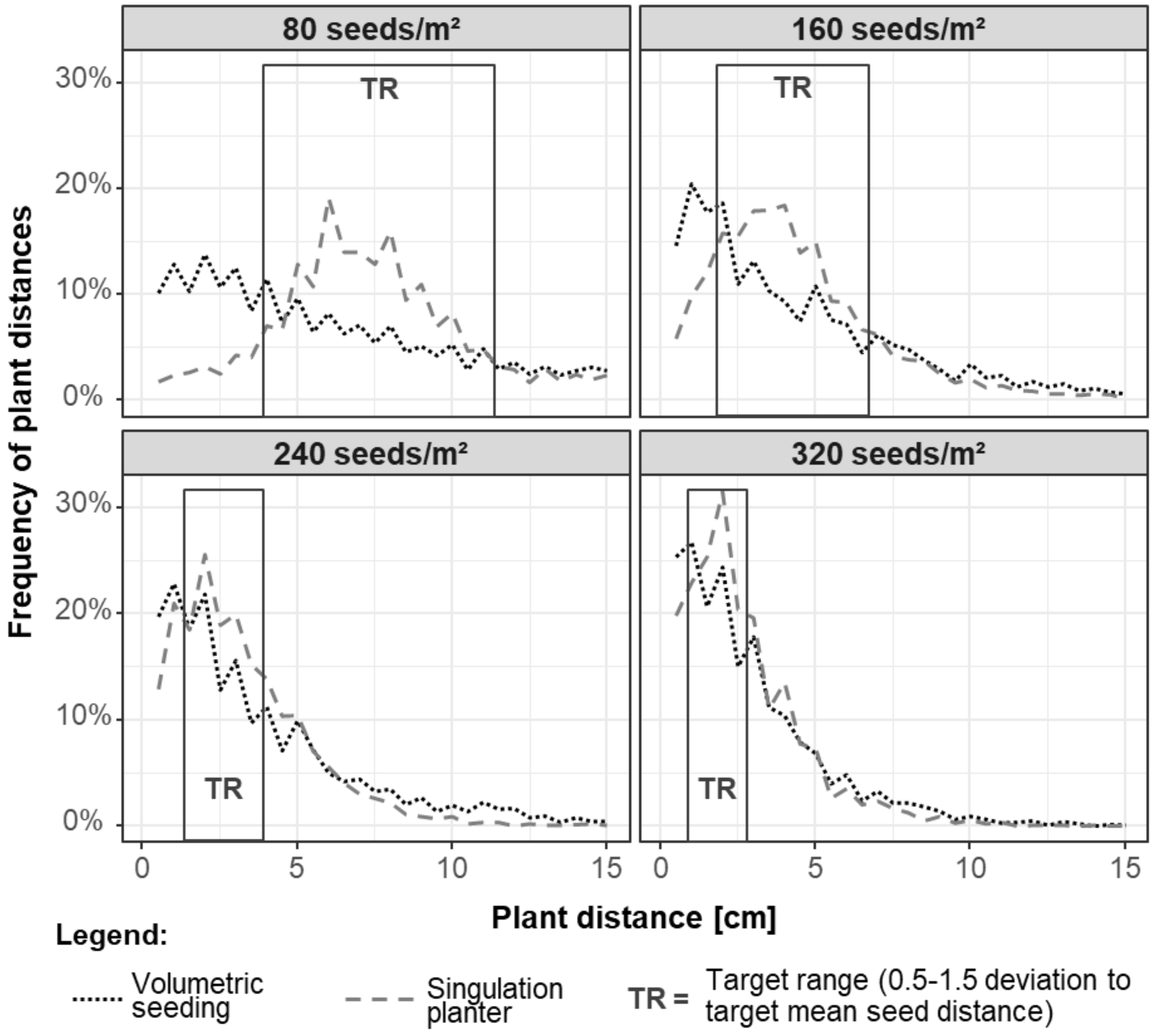

Figure 16: Frequency of winter wheat plant spacings for technique and seed rate, merged for variety and Test Site (GI19, OS19, GI20, OS20, FR20, HU20).

volumetric seeding (Table 8). This indicates a significantly improved plant distribution quality in trench when using the singulation planter. By fact, the CoV differs differently when comparing the individual seed rates to each other. At 80 seeds/m² the CoV of the singulation planter is 49 % lower compared to volumetric seeding. This difference is continuously getting lower when increasing the seed rate but still significant, resulting in a 16 % lower CoV at 320 seeds/m² when using the singulation planter. While the CoV of volumetric seeding is not influenced by seed rate, a significant raise of CoV when increasing the seed rate can be observed for the singulation planter.

Additional significance is also given for Test Site and its interaction to technique (Table 9). These differences might be a result of the differing emergence level of the Test Sites.

Besides using the CoV, a visualization of the plant spacing data within the histogram demonstrate the different reaction of the used seeding technique and its behavior when increasing seed rate (Figure 16). At all seed densities, the curve of volumetric seeding can be expressed by an exponential function, demonstrating high frequencies of plants staying to close to each other. Inversely the curve of the singulation planter follows a normal distribution with most plant distances ranging around the theoretical target mean seed distance of the specific seed rate. This effect can be clearly seen at 80 and 160 seeds/m² with tendency to an exponential function when seed rates exceed 240 seeds/m².

Table 10: Classification of winter wheat plant spacings in multiple, skipped and target placed seeds for technique and seed rate, merged over variety and Test Site (GI19, OS19, GI20, OS20, FR20, HU20).

	Classification of plant distances		
	Deviation to target mean seed distance		
	< 0.5	0.5 - 1.5	> 1.5
Seed rate & target mean seed distance in trench	**Multiple**	**Target range**	**Skip**
80 seeds/m² = 7.58 cm			
Volumetric seeding	33.6%	39.1%	27.3%
Singulation planter	10.2%	74.3%	15.5%
160 seeds/m² = 3.79 cm			
Volumetric seeding	28.5%	40.1%	31.5%
Singulation planter	15.1%	60.2%	24.6%
240 seeds/m² = 2.53 cm			
Volumetric seeding	25.3%	37.4%	37.3%
Singulation planter	19.1%	48.7%	32.1%
320 seeds/m² = 1.89 cm			
Volumetric seeding	20.3%	40.6%	39.1%
Singulation planter	15.5%	48.1%	36.3%

When defining the optimum target distance as a range of 0.5 to 1.5 deviation to target mean seed distance, the singulation planter hits the range with 35.2 % more seeds spaced at 80 seeds/m² and with 20.1 % more at 160 seeds/m² compared to volumetric seeding (Table 10). At the higher seed rates, the singulation planter still hits more seeds spaced in the optimum target range than the volumetric seeder but with decreasing improvement, resulting in 11.3 % more at 240 seeds/m² and 7.5 % more at 320 seeds/m². This corresponds to the peaks within the histogram and in addition to the increasing CoV when seed rates are increasing. Because of these data it can be stated that the singulation planter significantly improved the longitudinal plant distribution in trench through reducing the amount of missed and multiple seeds compared to volumetric seeding.

4.2 Crop development

Due to the assumption, that the tested factors seed rate and technique influence the intraspecific competition of winter wheat plants, the capability of producing tillers and ear bearing stems was examined during crop growth period in spring. As the same counting areas were used for plant density, tillering potential and ear development, these values were related to each other. Referring to tillering data it needs to be recognized that these data sets are limited as travel restrictions in spring 2020 prevent field trial visits and thus data evaluation. However, the ANOVA analysis indicates significant impact of seed rate and test site for tillers/m² and tillers/plant, while technique has significant impact on the number of tillers/plant with additional interacting potential to Test Site. When focusing on the tiller reduction rate, ensured significance is given for seed rate and Test Site. The number of ears/m² is significantly impacted by technique, seed rate and variety with additional interaction to Test Site. Comparing the number of ears per plant, significant potentials are mainly increased when interacting with the Test Site (Table 11).

Table 11: Effects of technique (Tec), seed rate (SR), variety (V) and Test Site (TS) on tiller density, number of tillers per plant, tiller reduction, ear density and number of ears per plant of winter wheat.

		Tiller density		**Tillers per plant**		**Tiller reduction**			**Ear density**		**Ears per plant**	
Factors	**NumDF**	F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)	**NumDF**	F value	Pr(>F)	F value	Pr(>F)
Tec	1	0.023	0.886	24.246	0.003 **	0.052	0.827	1	8.337	0.030 *	8.221	0.031 *
SR	3	26.039	< 0.001 ***	82.547	< 0.001 ***	17.793	< 0.001 ***	3	62.547	< 0.001 ***	282.289	< 0.001 ***
V	1	0.145	0.729	0.033	0.867	4.771	0.117	1	31.348	0.014 *	1.714	0.288
Tec x SR	3	0.334	0.801	0.787	0.503	0.408	0.748	3	0.255	0.858	0.448	0.719
Tec x V	1	0.064	0.809	0.109	0.753	0.000	0.992	1	0.040	0.849	0.066	0.807
SR x V	3	1.568	0.200	1.378	0.252	0.986	0.401	3	0.521	0.668	1.072	0.362
Tec x SR x V	3	1.084	0.358	0.253	0.859	0.817	0.487	3	0.338	0.798	0.445	0.721
TS	2	67.917	< 0.001 ***	166.302	< 0.001 ***	9.381	< 0.001 ***	5	205.224	< 0.001 ***	129.506	< 0.001 ***
Tec x TS	2	2.215	0.113	0.154	0.857	2.884	0.059 .	5	12.830	< 0.001 ***	4.549	< 0.001 ***
SR x TS	6	1.367	0.232	4.158	< 0.001 ***	1.112	0.359	15	3.014	< 0.001 ***	11.332	< 0.001 ***
V x TS	2	0.217	0.805	1.418	0.246	0.937	0.395	5	0.833	0.527	5.034	< 0.001 ***
Tec x SR x TS	6	2.108	0.056 .	1.042	0.401	1.869	0.091 .	15	1.015	0.440	2.502	0.002 **
Tec x V x TS	2	0.719	0.489	0.029	0.972	0.698	0.500	5	2.033	0.075 .	2.245	0.050 .
SR x V x TS	6	1.089	0.372	0.986	0.437	0.999	0.429	15	1.636	0.065 .	1.189	0.280
Tec x SR x V x TS	6	0.751	0.610	1.222	0.299	0.858	0.528	15	1.409	0.143	2.305	0.004 **

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

4.2.1 Tiller formation

When increasing the seed rate and thus plant density in field, tiller production per area and per plant are significantly impacted (Table 12). The results demonstrate that the number of tillers/m² increases at higher seed rates but with less impact. Doubling the seed rate from 80 to 160 seeds/m² produces 163 additional tillers/m², an additional doubling from 160 to 320 seeds/m² produces just 74 more additional tillers/m².

Inverse behavior is given for the number of tillers per plant. Here, doubling the seed rate from 80 to 160 seeds/m², reacts with 2.1 tillers less per plant, another doubling to 320 seeds/m² causes 1.2 tillers less per plant.

The tiller production per area is not influenced by technique, therefore the use of the singulation planter significantly creates 0.8 more tillers per plant. As the singulation planter tends in general to slightly lower emergence rates and as the emergence rate is also decreasing at higher seed densities, the number of tillers per plant might be better correlated to plant density in field than seed rate. Using the linear regression model as reference, seed rate and plant density are both significantly impacting the number of tillers per plant (Table 13). Due to a better model fit when using plant density as regression coefficient

Table 12: Average tiller density and number of tillers per plant at DC30, including tiller reduction for Test Site, technique, seed rate and variety. Values followed by a different letter are significantly different within columns ($p < 0.05$).

	Tiller formation (DC30)		
	No. of tillers per area [tillers/m²]	No. of tillers per plant	No. of reduced tillers per area [tillers/m²]
Test Site and year			
GI19	905 ^{B}	7.3 ^{C}	-394 ^{A}
GI20	639 ^{A}	3.9 ^{A}	-311 ^{B}
OS19	859 ^{B}	6.6 ^{B}	-370 ^{A}
Technique			
VS	800	5.5 ^{A}	-357
SP	803	6.3 ^{B}	-360
Seeds/m²			
80	656 ^{A}	8 ^{C}	-262 ^{B}
160	819 ^{B}	5.9 ^{B}	-377 ^{A}
240	837 ^{BC}	5.2 ^{A}	-372 ^{A}
320	893 ^{C}	4.7 ^{A}	-422 ^{A}
Variety			
HY	797	5.9	-376 ^{A}
NH	805	5.9	-341 ^{B}

(R^2 = 42.8 %) compared to seed rate (R^2 = 27.3 %), a higher explanatory level of plant density on tiller production is indicated.

Referring to reduced, unproductive tillers/m², significant higher reductions were detected for Test Site GI19 and OS19 and for variety hybrid, having 25 tillers more lost compared to non-hybrid (Table 12). Also, the amount of reduced tillers increases with higher seed rates. The low seed density of 80 seeds/m² reduces 110-160 tillers less compared to the other tested seed rates.

Table 13: Regression parameter of seed rate and plant density on number of tillers per plant, merged over all tested factors.

Regression analysis:	*Mod1: Y ~ Seed rate*	
	Mod2: Y ~ Plant density	
Variable (Y):	**Tillers/plant**	
	Mod1	*Mod2*
Seed rate	-0.013*** (0.002)	
Plant density		-0.022*** (0.002)
Constant	8.605*** (0.347)	9.676*** (0.339)
Observations	192	192
R^2	0.273	0.428
Adjusted R^2	0.270	0.425
Residual Std. Error (df = 190)	1,963	1,742
F Statistic (df = 1; 190)	71.493***	142.072***

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

4.2.2 Ear development

Technique, seed rate, variety and Test Site have significant impact on ear density (Table 11, Table 14). For all data, the number of ears/m² is increased by 25 when using the singulation planter. As technique is also interacting with Test Site, the detailed view of the boxplots visualizes that only in FR20 a significant higher amount of ears/m² was reached when using the singulation planter (Figure 17).

In general, the ear density is significantly increasing with higher seed rates. While the Test Sites GI19, GI20 and OS19 are less impacted with just 82-100 ears/m² difference between

Table 14: Average ear density and number of ears per plant for Test Site, technique, seed rate and variety. Values followed by a different letter are significantly different within columns ($p < 0.05$).

	Ear density	
	No. of ears per area [ears/m²]	No. of ears per plant
Test Site and year		
GI19	511 C	4.1 CD
GI20	328 A	2.1 A
OS19	489 C	3.8 C
OS20	635 D	4.3 D
FR20	405 B	3.8 C
HU20	350 A	2.6 B
Technique		
VS	441 A	3.4
SP	466 B	3.6
Seeds/m²		
80	381 A	5.1 D
160	447 B	3.4 C
240	478 C	2.9 B
320	507 D	2.5 A
Variety		
HY	435 A	3.4
NH	471 B	3.5

lowest to highest seed rate, a larger range of 154-196 ears/m² was identified in HU20, OS20 and FR20. These differences also proof the significant interaction of seed rate to Test Site (Table 11) and can also be seen when comparing the boxplots (Figure 17).

Winter wheat variety non-hybrid significantly produces 36 ears/m² more compared to hybrid. A comparable trend for the increased ear production of variety non-hybrid was also observed for the individual Test Sites.

Having a detailed look on the average ear density per Test Site, the German locations in Giessen and Oschersleben show large variations when comparing the test years. In test year 2019, ear density was not meaningful differing with 489 ears/m² in OS19 and 511 ears/m² in GI19. In the second field trial year, 183 ears/m² less were evaluated in GI20 and in contrary an increase of 146 ears/m² was evaluated in OS20. This resulted in a nearly 50 % lower ear density in GI20 compared to OS20. As these differences are additionally

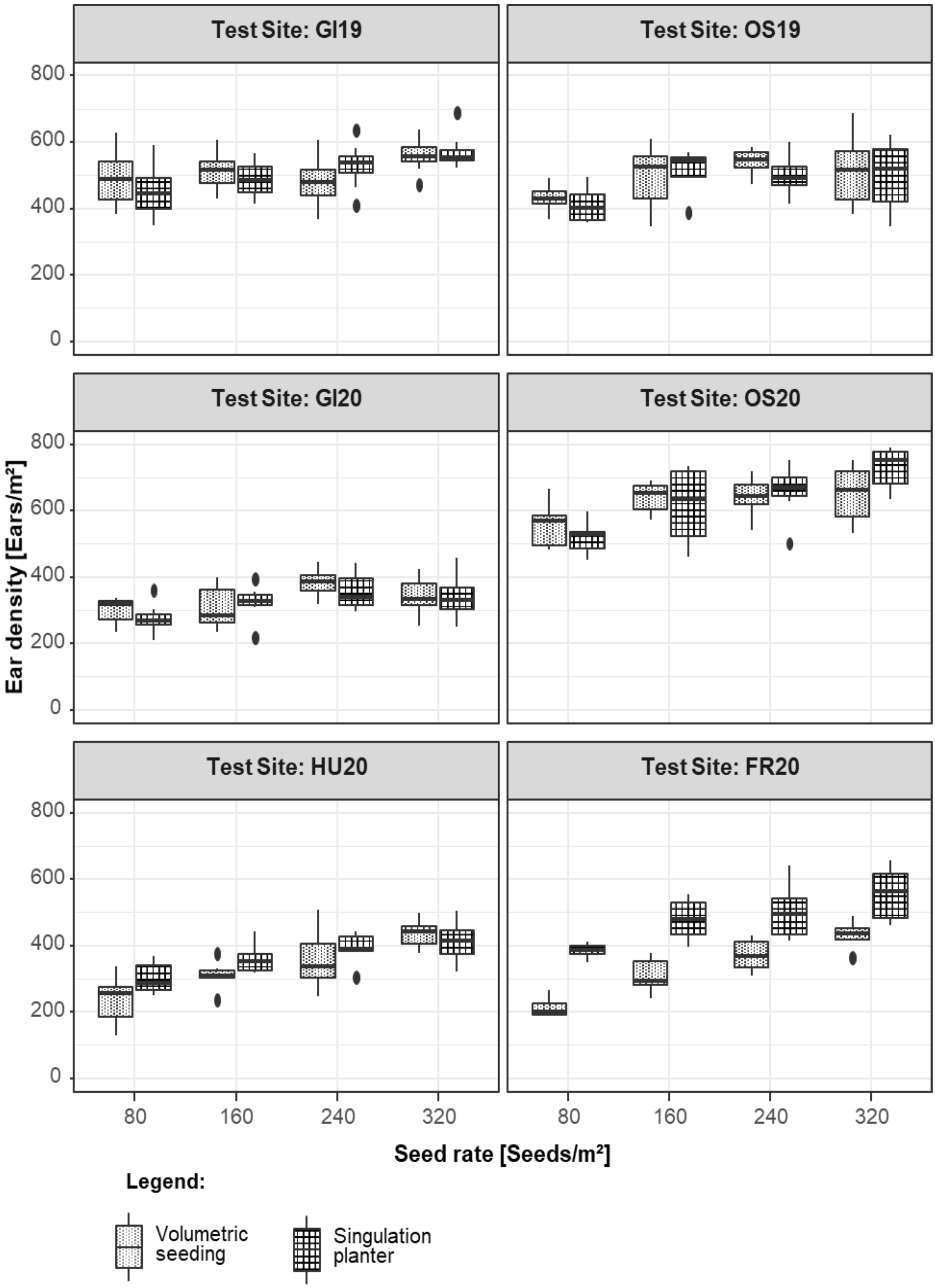

Figure 17: Ear density of winter wheat for Test Site depending on seed rate and technique, merged over variety.

differing to the ear density in FR20 and HU20, the Test Site specific weather and climate conditions need to be considered

In general, ear density is increasing with marginal return when using higher seed rates. This reaction of quadratic response is also significantly proven by the regression model but on a low explanatory level with R^2 = 10.4 %. An 8 % better explanatory level was realized after replacing seed rate by plant density (Table 15). Having the regression parameters as baseline, in average 125 plants/m² need to be established in field to realize an ear density of minimum 450 ears/m². The maximum density of 556 ears/m² can be reached with 288 plants/m².

Table 15: Regression parameter of seed rate and plant density and its quadratic response on ear density and number of ears per plant of winter wheat, merged over all factors.

Regression analysis:	*Mod1: Y ~ Seed rate + (Seed rate)²*			
	Mod2: Y ~ Plant density + (Plant density)²			
Variable (Y):	**Ears/m²**		**Ears/plant**	
	Mod1	*Mod2*	*Mod1*	*Mod2*
Seed rate	1.068*		-0.030***	
	(0.439)		(0.004)	
Seed rate²	-0.001		0.00005***	
	(0.001)		(0.00001)	
Plant density		2.301***		-0.028***
		(0.413)		(0.004)
Plant density²		-0.004***		0.00004***
		(0.001)		(0.00001)
Constant	315.410***	225.341***	7.110***	6.780***
	-38,496	-33,614	(0.357)	(0.312)
Observations	352	352	352	352
R^2	0.109	0.190	0.399	0.452
Adjusted R^2	0.104	0.185	0.395	0.448
Residual Std. Error (df = 349)	129,719	123,685	1,202	1,148
F Statistic (df = 2; 349)	21.291***	40.861***	115.762***	143.688***

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

For all data, the number of ears per plant significantly differs for seed rate and Test Site (Table 14). While the average ear production per plant is the highest at 80 seeds/m² (5.1 ears/plant), more than 50 % less ears per plant were indicated at 320 seeds/m² (2.5 ears/plant). The trend of less ears/plant at higher population densities can be also seen at the individual Test Sites, but with different reactions. While in GI19 the number of ears per plant is not any more differing between 160, 240 and 320 seeds/m², a much larger deviation can be seen in OS20. Here, the seed rate of 160 seeds/m² differs significantly to the lower and higher seed rates whereas the amount of ears/plant do not vary any more at 240 and 320 seeds/m². Referring to the technique specific reaction at the individual Test Sites, the singulation planter tends to increase the amount of ears/plant in GI19, OS19 and OS20. This effect can be clearly seen in the visualization as the boxplots of the singulation planter are mostly ranging above the boxplots of volumetric seeding (Figure 18). Only in HU20, the planter tends to decrease the amount of ears/plant. As there were already significant differences in emergence rate indicated (Table 7), it can be assumed that the number of ears/plant also depends on the plant density in field like it was already indicated for the number of tillers per plant. When following the results of the regression model (Table 15), the number of ears per plant is significantly impacted by seed rate and plant density, but the explanatory level of R^2 = 44.8 is 5.3 % higher when using measured plant density instead of seed rate as fixed factor.

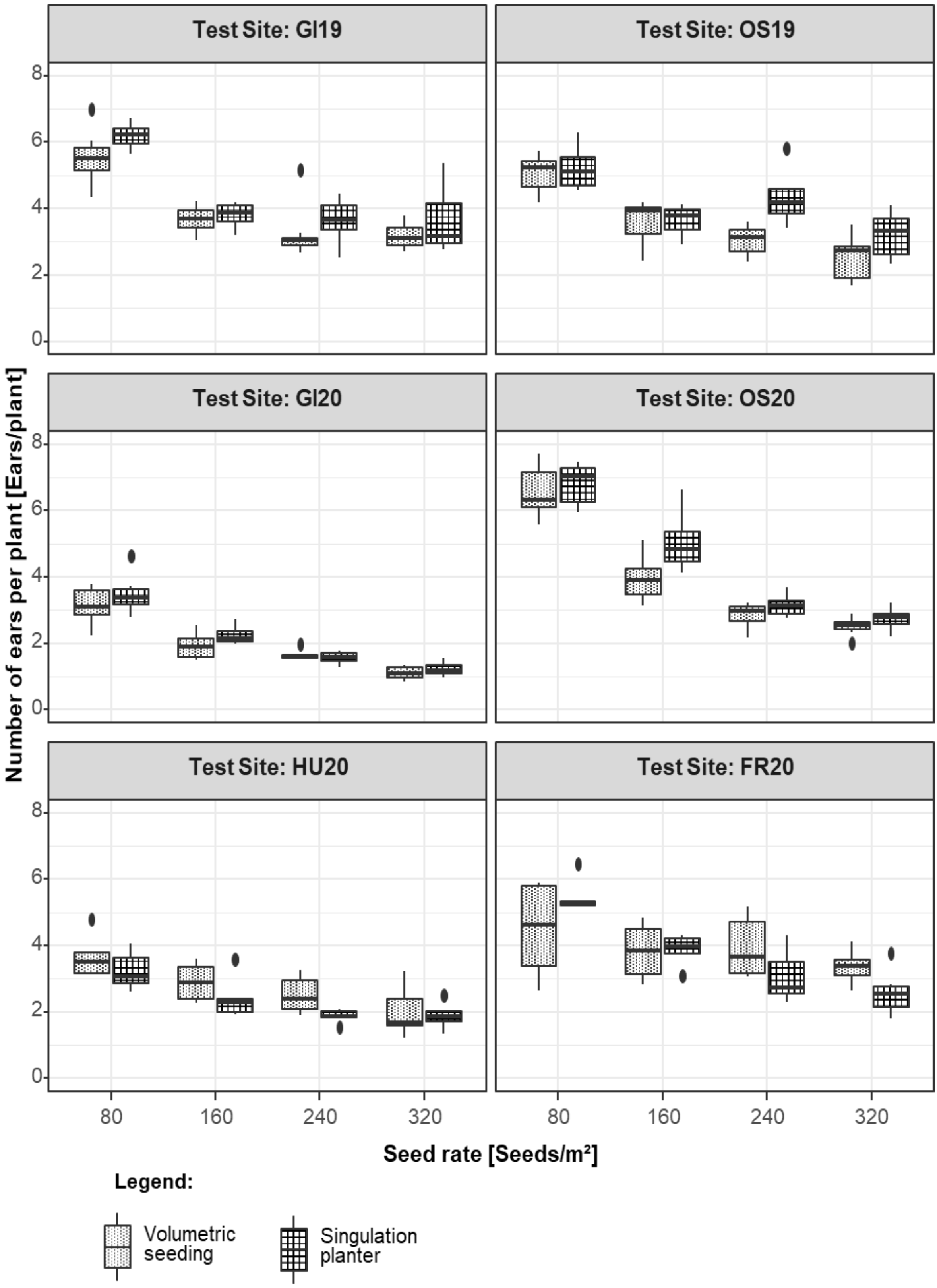

Figure 18: Number of ears per plant of winter wheat for Test Site depending on seed rate and technique, merged over variety.

4.3 Grain yield and grain yield structure

Referring to the hypotheses it is assumed that an improved plant placement quality in row when using a singulation planter can increase the crop yield production and that it delivers potential to maintain yield production at lower seed rates. Therefore, grain yield and the corresponding grain quality parameters were evaluated to verify the specific effects of the tested factors. The ANOVA analysis indicates significant impact for the tested factors and Test Sites on yield production and its corresponding yield forming and grain quality parameters (Table 16).

Table 16: Effects of technique (Tec), seed rate (SR), variety (V) and Test Site (TS) on winter wheat grain yield, thousand kernel weight (TKW), number of grains per ear and grain protein content.

		Grain yield		Thousand kernel weight		Grains per ear		Grain protein content	
Factors	NumDF	F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)	F value	Pr(>F)
Tec	1	31.062	0.002 **	6.981	0.042 *	1.034	0.352	11.698	0.016 *
SR	3	52.069	< 0.001 ***	0.295	0.829	16.134	< 0.001 ***	38.463	< 0.001 ***
V	1	0.245	0.656	64.062	0.005 **	50.339	< 0.001 **	64.588	0.005 **
Tec x SR	3	6.285	0.000 ***	0.238	0.870	0.565	0.638	2.072	0.105
Tec x V	1	1.469	0.274	1.160	0.326	0.180	0.687	0.202	0.670
SR x V	3	2.059	0.106	1.336	0.263	0.454	0.715	0.511	0.675
Tec x SR x V	3	0.239	0.869	3.321	0.020 *	1.664	0.175	0.280	0.840
TS	5	563.824	< 0.001 ***	866.015	< 0.001 ***	78.220	< 0.001 ***	1173.198	< 0.001 ***
Tec x TS	5	7.901	< 0.001 ***	3.824	0.002 **	9.521	< 0.001 ***	1.423	0.217
SR x TS	15	8.451	< 0.001 ***	5.452	< 0.001 ***	1.559	0.086 .	3.209	< 0.001 ***
V x TS	5	4.131	0.001 **	5.940	< 0.001 ***	1.533	0.180	5.030	< 0.001 ***
Tec x SR x TS	15	1.663	0.059 .	1.177	0.290	1.223	0.255	1.328	0.186
Tec x V x TS	5	2.822	0.017 *	1.210	0.305	1.612	0.158	0.558	0.732
SR x V x TS	15	1.057	0.398	1.299	0.203	1.486	0.111	0.497	0.941
Tec x SR x V x TS	15	0.796	0.682	1.079	0.377	1.287	0.210	0.800	0.677

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

4.3.1 Grain yield

The variation of yield production is significantly different between the Test Sites (Table 17). A comparable yield level was achieved in FR20 (8.18 t/ha) and HU20 (8.01 t/ha). Within both Test years in Giessen, substantial higher yields were realized with 10.61 t/ha in GI19 and 10.27 t/h in GI20. In contrary to Giessen, yield production in Oschersleben was highly differing with 6.48 t/ha in OS19 and 11.66 t/ha in OS20.

Over all data, technique singulation planter produces meaningful higher yields by 0.48 t/ha more compared to volumetric seeding (Table 17). Except OS20, singulation planter has increased yield at all Test Sites but significantly differing are only GI20, HU20 and FR20.

Table 17: Average winter wheat grain yield of the Test Sites for technique, variety and seed rate. Values followed by a different letter are significantly different within columns ($p < 0.05$).

	Grain yield of Test Sites [t/ha]						
	GI19	OS19	GI20	OS20	HU20	FR20	**Mean**
Technique							
VS	10.49	6.40	10.04 ^{A}	11.70	7.64 ^{A}	7.50 ^{A}	8.96 ^{A}
SP	10.73	6.55	10.51 ^{B}	11.61	8.38 ^{B}	8.85 ^{B}	9.44 ^{B}
Seeds/m²							
80	10.40	6.33	9.92 ^{A}	11.13 ^{A}	6.41 ^{A}	6.47 ^{A}	8.44 ^{A}
160	10.52	6.55	10.07 ^{A}	11.59 ^{AB}	7.94 ^{BC}	8.25 ^{B}	9.16 ^{B}
240	10.74	6.48	10.68 ^{B}	11.98 ^{B}	8.60 ^{BC}	9.08 ^{C}	9.59 ^{C}
320	10.80	6.54	10.40 ^{AB}	11.92 ^{B}	9.09 ^{C}	8.91 ^{BC}	9.61 ^{C}
Variety							
HY	10.39 ^{A}	6.41	10.49 ^{B}	11.81	8.13	8.15	9.23
NH	10.83 ^{B}	6.54	10.05 ^{A}	11.51	7.89	8.20	9.17

Focusing on the significant interaction of technique to seed rate, a lower sensitivity in yield production across the seed rates is given when using the singulation planter (Table 18). The lowest yield for the singulation planter was measured at 80 seeds/m² and the highest at 240 seeds/m², having a yield difference of 0.84 t/ha. Compared to volumetric seeding, the yield level between lowest and highest seed rate differs in a higher range by 1.58 t/ha. Here, a significant higher yield loss can be seen when seed rate falls below 240 seeds/m². A comparable significant yield reduction has been recognized for the singulation planter when seed rates drop below 160 seeds/m². With this indication, the singulation planter can achieve the same yield level at lower seed rates, compared to volumetric seeding.

Table 18: Average grain yield of factor technique depending on seed rate, merged over variety and Test Site. Values followed by a different letter are significantly different within columns and rows and for mean in row ($p < 0.05$).

	Grain yield of technique [t/ha]	
Seeds/m²	Volumetric seeding	Singulation planter
80	8.00 ^{A}	8.89 ^{B}
160	8.81 ^{B}	9.50 ^{C}
240	9.45 ^{C}	9.73 ^{C}
320	9.58 ^{C}	9.64 ^{C}
Mean	8.96 ^{A}	9.44 ^{B}

A detailed view on seed rate proofs that yield increases when seed rates are getting higher (Table 17). In total, yield increases by 1.2 t/ha when seed rate is increased from 80 to 320 seeds/m². Having a specific focus on the Test Sites, this ratio is mainly leveraged by FR20 and HU20, as the yield ranges from lowest to highest density by 2.7 t/ha in HU20 and 2.4 t/ha in FR20. This range is lower with 0.8 t/ha in OS20 and 0.5 t/ha in GI20 but still significantly differing. No meaningful impact is given by GI19 (0.4 t/ha between lowest to highest seed rate) and OS19 (0.2 t/ha between lowest to highest seed rate). This differing yield reaction fits also to the significant interaction of seed rate and Test Site, indicated by the ANOVA (Table 16).

For factor variety, significant yield difference is given when interacting with Test Site (Table 17). This meaningful difference can be only indicated at both test years in Giessen. Interestingly, an inverse reaction between GI19 and GI20 is given. While winter wheat variety non-hybrid produced 0.4 t/ha more yield in the first year compared to variety hybrid, hybrid was yielding 0.5 t/ha more in the second year compared to non-hybrid. A similar inverse trend can be seen between the other Test Sites, as non-hybrid wheat tends to higher yields in OS19 and FR20 whereas hybrid wheat tends to produce higher yields in OS20 and HU20. However, a meaningful variety specific yield trend is not given.

4.3.2 Thousand kernel weight

Merging the data of thousand kernel weight (TKW) above Test Site, significant higher TKW was detected for technique singulation planter and variety non-hybrid. As the Test Site is strong significantly impacting TKW, specific interactions of Test Site to technique, seed rate and variety were found (Table 19). Except FR20 and GI20, variety non-hybrid generated significant higher TKW at the other Test Sites, with lowest difference of 1.2 g higher TKW in OS19 and 2.9 g higher TKW in HU20. When comparing the reaction of seed rate within the individual Test Sites, no clear impact on TKW was found. However, OS19, OS20, GI20, HU20 tend to lower TKW when seed rate is increasing. In contrary, GI19 and FR20 reacted with higher TKW at increased seed rates.

Table 19: Average winter wheat thousand kernel weight (TKW) of the Test Sites for technique, variety and seed rate. Values followed by a different letter are significantly different within columns and for mean of Test Sites within row ($p < 0.05$).

	Thousand kernel weight of Test Sites [g]						
	GI19	OS19	GI20	OS20	HU20	FR20	**Mean**
Technique							
VS	39.9 ^{A}	35.5 ^{A}	54.6 ^{A}	47.7 ^{A}	48.7 ^{A}	38.7 ^{A}	44.2 ^{A}
SP	40.8 ^{B}	36.5 ^{B}	54.1 ^{A}	47.7 ^{A}	48.3 ^{A}	40.8 ^{B}	44.7 ^{B}
Seeds/m²							
80	39.7 ^{A}	37.2 ^{B}	54.4 ^{A}	48.1 ^{A}	49.4 ^{A}	37.2 ^{A}	44.3
160	40.2 ^{A}	36.3 ^{AB}	54.6 ^{A}	48.2 ^{A}	48.7 ^{A}	38.7 ^{A}	44.4
240	40.4 ^{A}	35.1 ^{A}	54.3 ^{A}	47.7 ^{A}	48.2 ^{A}	42.0 ^{B}	44.6
320	41.1 ^{A}	35.5 ^{AB}	54.0 ^{A}	46.9 ^{A}	47.6 ^{A}	41.0 ^{B}	44.3
Variety							
HY	39.1 ^{A}	35.4 ^{A}	54.5 ^{A}	46.6 ^{A}	47.0 ^{A}	39.2 ^{A}	43.6 ^{A}
NH	41.5 ^{B}	36.6 ^{B}	54.2 ^{A}	48.8 ^{B}	49.9 ^{B}	40.3 ^{A}	45.2 ^{B}
Mean	40.3 ^{B}	36 ^{A}	54.3 ^{D}	47.7 ^{C}	47.9 ^{C}	39.7 ^{B}	

4.3.3 Number of grains per ear

The number of produced grains per ear significantly varies between the Test Sites (Table 20). In Oschersleben, the lowest grain number per ear was calculated with 37.6 in OS20 and 39.4 in OS20. Highest grain production per ear was in average produced in GI20 with 59.4 grains/ear.

In total average, the grain number per ear is not influenced by technique. However, a significant interaction to Test Site indicates differing impact (Table 20). While the grain number per ear is not impacted in GI19, OS19, OS20 and HU20, technique singulation planter produces in GI20 significantly 5.2 more grains per ear compared to volumetric seeding. In contrary, volumetric seeding produces in average 14.2 more grains per ear in FR20.

Test factor seed rate also drives the grain number per ear, a significant decreasing trend is given when seed rates are getting higher (Table 20). A similar decreasing trend is given for the individual Test Sites, only OS19 and HU20 are not significantly impacted when seed rate changes. This response fits to the low significant level (alpha < 0.1) of the interaction seed rate to Test Site, that was indicated by the ANOVA (Table 16).

The wheat variety hybrid significantly produces 5.9 grains per ear more than variety non-hybrid. The same trend can be seen for the individual Test Sites (Table 20).

Table 20: Average grain number per ear for winter wheat of the Test Sites for technique, variety and seed rate. Values followed by a different letter are significantly different within columns and for mean of Test Sites within row ($p < 0.05$).

	Grain number per ear of Test Sites [grains/ear]						
	GI19	OS19	GI20	OS20	HU20	FR20	**Mean**
Technique							
VS	52.7 A	37.2 A	56.8 A	39.0 A	49.9 A	61.8 B	49.6
SP	52.7 A	38.0 A	62.0 B	39.9 A	48.7 A	47.7 A	48.2
Seeds/m²							
80	57.0 B	40.9 A	64.9 B	43.6 B	51.1 A	61.9 C	53.3 C
160	53.2 AB	36.2 A	60.2 AB	39.4 AB	49.9 A	57.4 BC	49.4 B
240	53.6 AB	35.8 A	54.1 A	38.6 AB	49.9 A	52.9 AB	47.5 AB
320	47.1 A	37.5 A	58.3 AB	36.2 A	46.3 A	46.7 A	45.3 A
Variety							
HY	56.2 B	39.4 A	63.8 B	42.2 B	53.2 B	55.9 A	51.8 B
NH	49.2 A	35.9 A	55.0 A	36.7 A	45.4 A	53.6 A	45.9 A
Mean	52.7 BC	37.6 A	59.4 D	39.4 A	49.3 B	54.7 C	

4.3.4 Yield related traits

Yield production can be expressed in a linear model by ear density (ears/m²), grain weight (TKW) and the grain number per ear (grains/ear). The adjusted R^2 of 88 % proofs a high explanatory level of these three components (Table 21).

Using the previously evaluated results, a significantly higher ear density (+25 ears/m²; (Table 14)) and a significant higher grain weight (+0.5 g; (Table 19)) can be reached when using the singulation planter. Only grain number per ear is negative correlated (-1.4 grains/ear; (Table 20)) but not significantly differing.

Putting these data into the regression model, the average yield increase of the singulation planter can be explained by 0.5 t/ha more affected by the higher ear density and additionally 0.09 t/ha more due to the higher grain weight. The lower grain number per ear causes a yield decrease of 0.19 t/ha. However, the positive yield effect of ear density and grain weight compensate the negative yield effect of less grains per ear resulting in theoretically 0.4 t/ha higher yield production in average when using the singulation planter. This result fits closely

Table 21: Regression parameter of winter wheat grain yield and its dependency on thousand kernel weight (TKW), Ear density and grain number per ear, merged over all factors and Test Sites (GI19, OS19, GI20, OS20, FR20, HU20).

Regression analysis: *Yield ~ TKW + Ears/m² + Grains/ear*			
Predictors	*Estimates*	*CI*	*p*
(Intercept)	-13.84	-14.76 – -12.92	**<0.001**
TKW	0.18	0.17 – 0.19	**<0.001**
Ears/m²	0.02	0.02 – 0.02	**<0.001**
Grains/ear	0.14	0.14 – 0.15	**<0.001**
Observations	350		
R^2 / R^2 adjusted	0.881 / 0.880		

to the in field experiment measured 0.48 t/ha higher yield (Table 17) when using the singulation planter. All in all, the higher yield production of the singulation planter is mainly driven by the higher ear density and in addition by the slightly higher grain weight.

4.4 Grain protein content

Protein content is significantly reduced when using technique singulation planter, high seed rates and wheat variety hybrid (Table 22). In total average, protein contents above 12 % can be achieved when using volumetric seed metering, at a low seed rate of 80 seeds/m²

Table 22: Grain protein content for winter wheat of the Test Sites for technique, variety and seed rate. Values followed by a different letter are significantly different within columns and for mean of Test Sites within row ($p < 0.05$).

	Grain protein content of Test Sites [%]						
	GI19	OS19	GI20	OS20	HU20	FR20	**Mean**
Technique							
VS	9.8 A	14.8 B	10.2 A	11.8 A	12.4 A	13.4 B	12.1 B
SP	9.8 A	14.5 A	10.1 A	11.7 A	12.3 A	13.0 A	11.9 A
Seeds/m²							
80	10.4 B	15.0 B	10.8 C	12.1 B	12.4 A	13.4 A	12.4 B
160	9.5 A	14.6 AB	10.3 B	11.8 AB	12.2 A	13.1 A	11.9 A
240	9.7 A	14.6 AB	9.9 AB	11.6 A	12.4 A	13.0 A	11.9 A
320	9.4 A	14.5 A	9.7 A	11.5 A	12.3 A	13.3 A	11.8 A
Variety							
HY	9.4 A	14.6 A	9.9 A	11.6 A	12.2 A	13.1 A	11.8 A
NH	10.2 B	14.7 A	10.4 B	11.9 B	12.5 B	13.3 A	12.2 B
Mean	9.8 A	14.7 F	10.2 B	11.8 C	12.3 D	13.2 E	

and the wheat variety non-hybrid. Comparing the average protein content of the Test Sites, FR20, HU20 and OS19 exceed the protein content of 12 %. In contrary, GI19 and GI20 generated the lowest protein content (9.8 and 10.2 %). Due to the Test Site specific different protein contents, significant interactions were detected for seed rate and variety (Table 16). A clear significant reduction in protein content when increasing the seed rate was detected in GI19, GI20, OS19 and OS20 while FR20 and HU20 showed no reaction on seed rate. When comparing the reaction of variety for the specific Test Sites, there is no meaningful impact on protein content in OS19 and FR20. Nevertheless, the protein level at these two locations is slightly higher for wheat variety non-hybrid so the reaction follows the trend of increased protein content when using variety non-hybrid.

When reviewing the yield effects of the tested factors, comparable significant reaction on technique, seed rate, variety and Test Site can be detected. Here, the contribution of protein content to yield proves a negative correlation (Figure 19). Over all data, each produced ton of grain yield reduces the protein content by 0.65 %. As there is a high model fit of 53 %, this fits to the in average lower yields and the higher protein contents when using technique volumetric seeding, wheat variety non-hybrid and low seed densities.

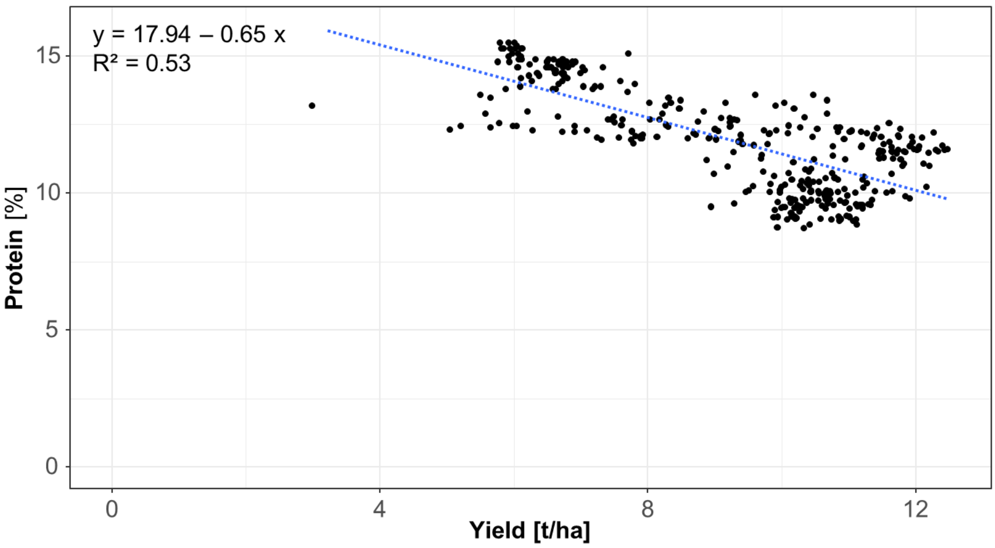

Figure 19: The relationship between grain yield and grain protein content of winter wheat. Data points include all evaluated yield and protein data.

4.5 Yield regression modeling

The previous results have shown already that yield level is influenced by the factors technique, seed rate, variety and Test Site. To estimate the specific yield curve of these individual combinations and their interactions a linear regression model was used, implementing seed rate as quadratic response. The regression summary shows significant model fit for the individual Test Sites (Table 23), instead of OS19. The negative R^2 indicates

Table 23: Winter wheat grain yield regression parameters for the individual Test Sites, depending on singulation planter (SP), seed rate (SR), seed rate as squared response (SR2) and variety non-hybrid (NH).

Regression analysis: *Yield ~ Technique * Seed rate * Variety + (Seed rate)²*

	GI19	GI20	OS19	OS20	FR20	HU20
SP	-0.162 (0.472)	**0.820$^{.}$** **(0.462)**	0.167 (0.424)	0.379 (0.389)	**3.832**** **-1,271**	**2.664***** **(0.537)**
SR	0.001 (0.005)	**0.012*** **(0.004)**	0.004 (0.004)	**0.012**** **(0.004)**	**0.048***** **(0.012)**	**0.033***** **(0.005)**
NH	-0.301 (0.472)	**-0.775$^{.}$** **(0.462)**	0.224 (0.424)	-0.042 (0.389)	1,649 -1,271	**1.423*** **(0.537)**
SR²	-0.00000 (0.00001)	-0.00002 (0.00001)	-0.00001 (0.00001)	**-0.00002*** **(0.00001)**	**-0.0001*** **(0.00003)**	**-0.00004**** **(0.00001)**
SP x SR	0.003 (0.002)	-0.003 (0.002)	-0.0004 (0.002)	-0.001 (0.002)	**-0.011$^{.}$** **(0.006)**	**-0.007**** **(0.002)**
SP x NH	**1.241$^{.}$** **(0.668)**	**1.162$^{.}$** **(0.653)**	0.078 (0.600)	-0.562 (0.550)	-1,594 -1,814	**-1.534$^{.}$** **(0.760)**
SR x NH	**0.004*** **(0.002)**	-0.0001 (0.002)	-0.001 (0.002)	-0.00001 (0.002)	-0.006 (0.006)	**-0.006*** **(0.002)**
SP x SR x NH	**-0.007*** **(0.003)**	-0.002 (0.003)	0.0001 (0.003)	0.0002 (0.003)	0.005 (0.008)	0.003 (0.003)
Constant	**10.108***** **(0.477)**	**8.909***** **(0.466)**	**5.930***** **(0.428)**	**10.303***** **(0.393)**	1,414 -1,302	**2.927***** **(0.543)**
Observations	64	64	64	64	46	48
R^2	0.327	0.503	0.073	0.469	0.578	0.850
Adjusted R^2	0.230	0.431	-0.062	0.391	0.487	0.819
Residual Std. Error	0.545 (df = 55)	0.533 (df = 55)	0.490 (df = 55)	0.449 (df = 55)	1,271 (df = 37)	0.537 (df = 39)
F Statistic	3.347** (df = 8; 55)	6.955*** (df = 8; 55)	0.542 (df = 8; 55)	6.064*** (df = 8; 55)	6.330*** (df = 8; 37)	27.530*** (df = 8; 39)

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

that the use of this model for explaining yield in OS19 is not fully given. Additionally, the adjusted R^2 of 23 % in GI19 delivers a low model explanation. Having a model fit of R^2 with minimum 39 %, a much better model fit was generated at the other Test Sites. Using the model over all Test Sites, significance of the model is given but on a low explanatory level with R^2 = 4 %. After including the factor Test Site as dummy variable, an increased model fit of 85 % can be realized and a higher significance level also (Table 24).

Within the regression coefficients, the positive values for technique singulation planter indicate a yield increasing effect, that is also significant for GI20, FR20 and HU20. In contrary a negative interaction of singulation planter to seed rate indicate a marginal return in yield increase when seed rates are getting higher (Table 23).

Only in GI19 the singulation planter has negative yield impact but on a low level of -0.162 t/ha. Therefore, the positive interaction term of singulation planter to seed rate compensates the negative constant of the singulation planter (Table 23).

Factor seed rate is positive correlated for all individual Test Sites, only in GI19 and OS19 no significant effect for seed rate is given. The negative term of seed rate squared indicates decreasing yield response when seed rates are getting higher.

Within the regression parameter, factor variety and its interaction to seed rate and/or technique planter show no clear trend for the individual Test Sites as the regression coefficients differ with negative and positive values (Table 23). Using instead the regression merged over all Test Sites, wheat yield of variety non-hybrid is positively correlated, but negative values in the interaction terms reduce its effect. The use of technique singulation planter and high seed rates tend to decrease the yield effect of variety non-hybrid (Table 24).

Table 24: Average winter wheat grain yield regression parameters over Test Site, depending on singulation planter (SP), seed rate (SR), seed rate as squared response (SR2) and variety non-hybrid, considering Test Site as dummy variable.

Regression analysis: *Yield ~ Technique * Seed rate * Variety + (Seed rate)²*		
	All data	All data + Test Site as dummy variable
SP	1.104 (0.744)	**1.104***** **(0.299)**
SR	**0.016*** **(0.007)**	**0.016***** **(0.003)**
NH	0.256 (0.744)	0.256 (0.299)
SR²	-0.00002 (0.00002)	**-0.00002***** **(0.00001)**
GI19		**2.408***** **(0.156)**
GI20		**2.066***** **(0.156)**
HU20		-0.147 (0.167)
OS19		**-1.729***** **(0.156)**
OS20		**3.452***** **(0.156)**
SP x SR	-0.003 (0.003)	**-0.003*** **(0.001)**
SP x NH	-0.089 -1,054	-0.063 (0.423)
SR x NH	-0.001 (0.003)	-0.001 (0.001)
SP x SR x NH	-0.001 (0.005)	-0.001 (0.002)
Constant	**7.006***** **(0.753)**	**5.899***** **(0.322)**
Observations	350	350
R^2	0.061	0.851
Adjusted R^2	0.038	0.845
Residual Std. Error	2.016 (df = 341)	0.809 (df = 336)
F Statistic	2.746** (df = 8; 341)	147.510*** (df = 13; 336)

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

4.5.1 Agronomic and economic optimum yield levels

Using the regression parameters as input, the agronomic yield curve of the specific reaction of technique and variety in terms of seed rate were drawn for each individual Test Site and for all data merged over the Test Sites (Figure 20, Figure 21, Figure 24). The economic yield curve demonstrates the gross margin, reflecting only yield income minus seed costs per hectare (Figure 22, Figure 23, Figure 25). These values are derived by the agronomic yield curve.

When analyzing the maximum agronomic yield production for each curve (Table 25), the use of the singulation planter has a higher potential for yield generation compared to volumetric seeding. Highest wheat yield can be only achieved with volumetric seeding for variety non-hybrid in GI19 (+ 0.69 t/ha), OS20 (+ 0.41 t/ha) and HU20 (+ 0.23 t/ha) and for variety hybrid in GI20 (+ 0.2 t/ha). Interestingly, the singulation planter reaches the maximum yield level constantly at lower seed rates compared to volumetric seeding with the exception of GI19. The largest differing seed rates when using the singulation planter were identified in GI20, HU20 and FR20. This reduction seems to be stronger for hybrid wheat (GI20: 103 seeds; HU20: 90 seeds; FR20: 73 seeds less compared to volumetric seeding) compared to non-hybrid wheat (GI20: 74 seeds; HU20: 64 seeds; FR20: 27 seeds less compared to volumetric seeding). In OS19 and OS20 the maximum yield production can be reached with the singulation planter at 20-30 seeds/m² less compared to volumetric seeding.

The comparison of the maximum agronomic yield levels within the merged data demonstrates that the use of the singulation planter generates in non-hybrid wheat 0.04 t/ha more yield while saving 76 seeds/m². For hybrid wheat, 0.2 t/ha yield increase at a 62 seeds/m² lower seed rate can be achieved with the singulation planter (Table 25).

In contrast to the agronomic optimum yield production, the maximum monetary value is generally reached at lower seed densities and thus lower yield while monetary yield loss is compensated by seed cost savings. When comparing the behavior of the economic and agronomic curves, the optimum seed rate is much more reduced to lower seed densities when using hybrid wheat seeds. This effect can be seen at all Test Sites. Focusing on the merged regression curve (Figure 24, Figure 25), the economic optimum seed rate is 156 seeds/m² less for hybrid wheat and 23 seeds/m² less for non-hybrid wheat in contrast to agronomic optimum yield (Table 25).

In GI19, GI20 and OS19, the calculated economic optimum seed rate for hybrid wheat declared values close to zero or in a negative range. To keep the agronomic confidentiality, a minimum seed rate estimate of 50 seeds/m² and a maximum seed rate estimate of 400 seeds/m² was used if the calculated values were out of this range.

Referring the monetary value using the gross margin of yield income at given seed costs, an increased income differing between the Test Sites of 0.79 €/ha – 9.08 €/ha for non-

hybrid wheat and 33.20 €/ha – 264.48 €/ha for hybrid wheat can be realized when adjusting the seed rates from agronomic to economic optimum (Table 25). With focus on the gross margin of both tested varieties, hybrid wheat differs with 106.75 €/ha – 252.65 €/ha less economic benefit compared to non-hybrid wheat between the Test Sites. Increased economic advantage can be generated when using technique singulation planter instead of volumetric seeding. This effect tends to be additionally higher when using hybrid wheat. In range of the Test Sites, the singulation planter generates 26.64 – 229.29 €/ha higher income when using hybrid wheat. Only at Test Site GI19 the planter delivers a -5.21 €/ha lower income with variety hybrid. When using non-hybrid wheat, the planter cannot generate additional income at Test Sites GI19 (-55.46 €/ha), OS20 (-69.84 €/ha) and HU20 (-30.57 €/ha). Therefore, the income can be increased for singulation planter and non-hybrid in GI20 (120.66 €/ha), OS19 (37.86 €/ha) and FR20 (154.26 €/ha).
Referring these specifications on the merged regression data of all Test Site data (Figure 24 and 25), the economic optimum of hybrid wheat is 224.65 €/ha lower compared to non-hybrid wheat. Also, the use of the singulation planter can produce additional income with 22.19 €/ha more for non-hybrid wheat and 119.28 €/ha more for hybrid wheat (Table 25).

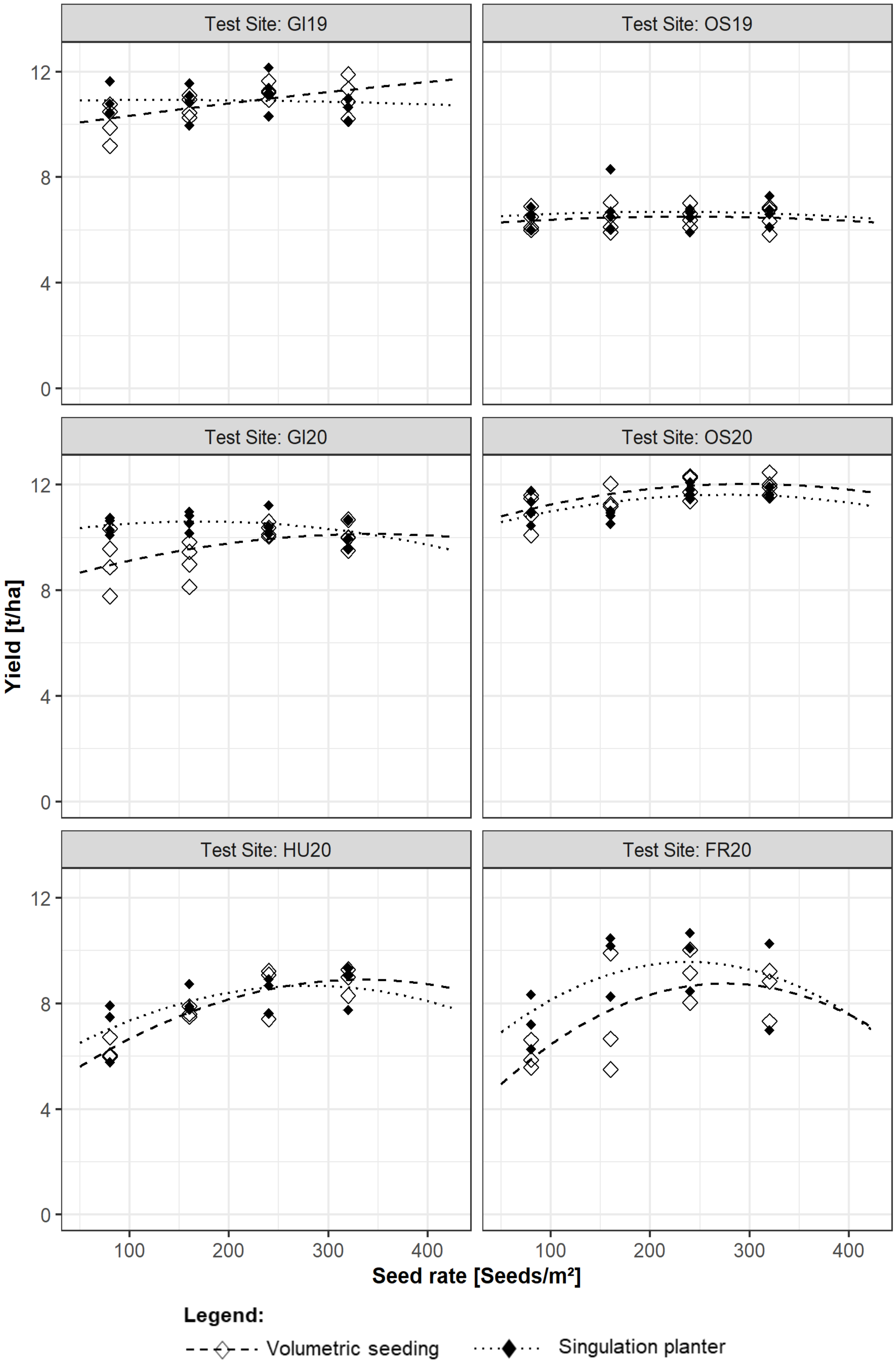

Figure 20: Agronomic winter wheat yield curve of variety non-hybrid for Test Site, depending on seed rate and technique.

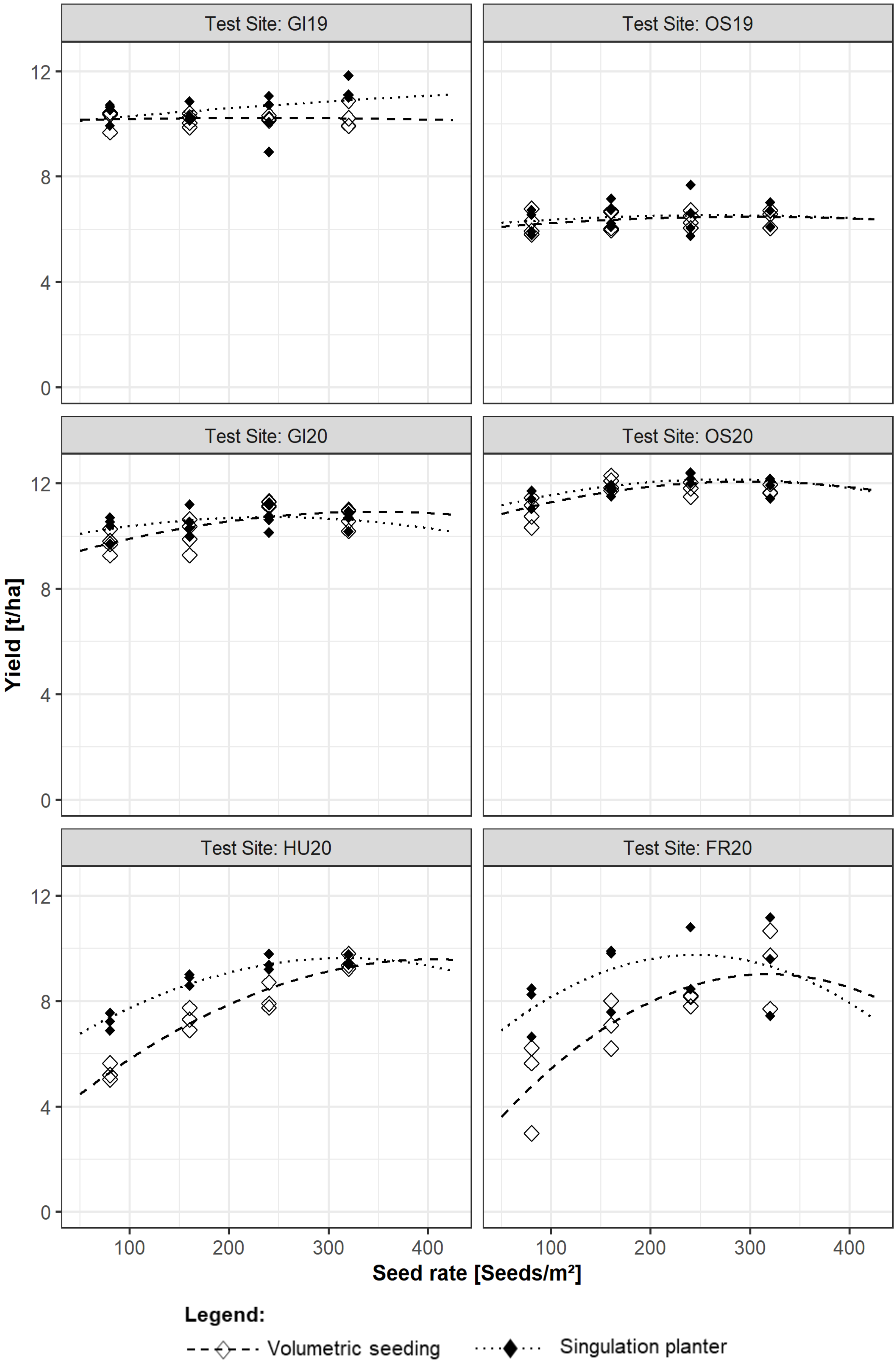

Figure 21: Agronomic winter wheat yield curve of variety hybrid for Test Site, depending on seed rate and technique.

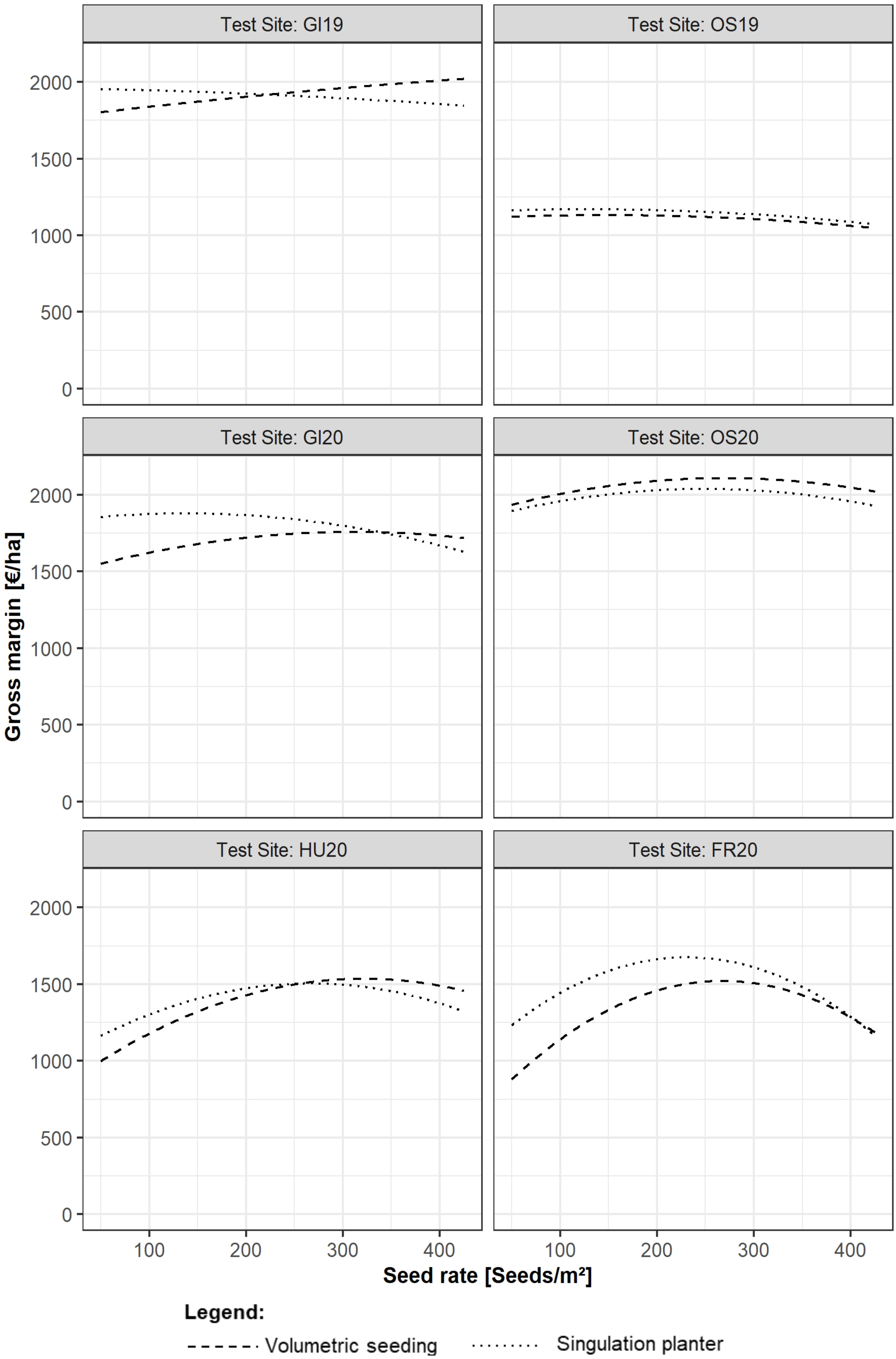

Figure 22: Economic response (gross margin) of winter wheat yield curve in terms of market price and seed costs of variety non-hybrid for Test Site, depending on seed rate and technique.

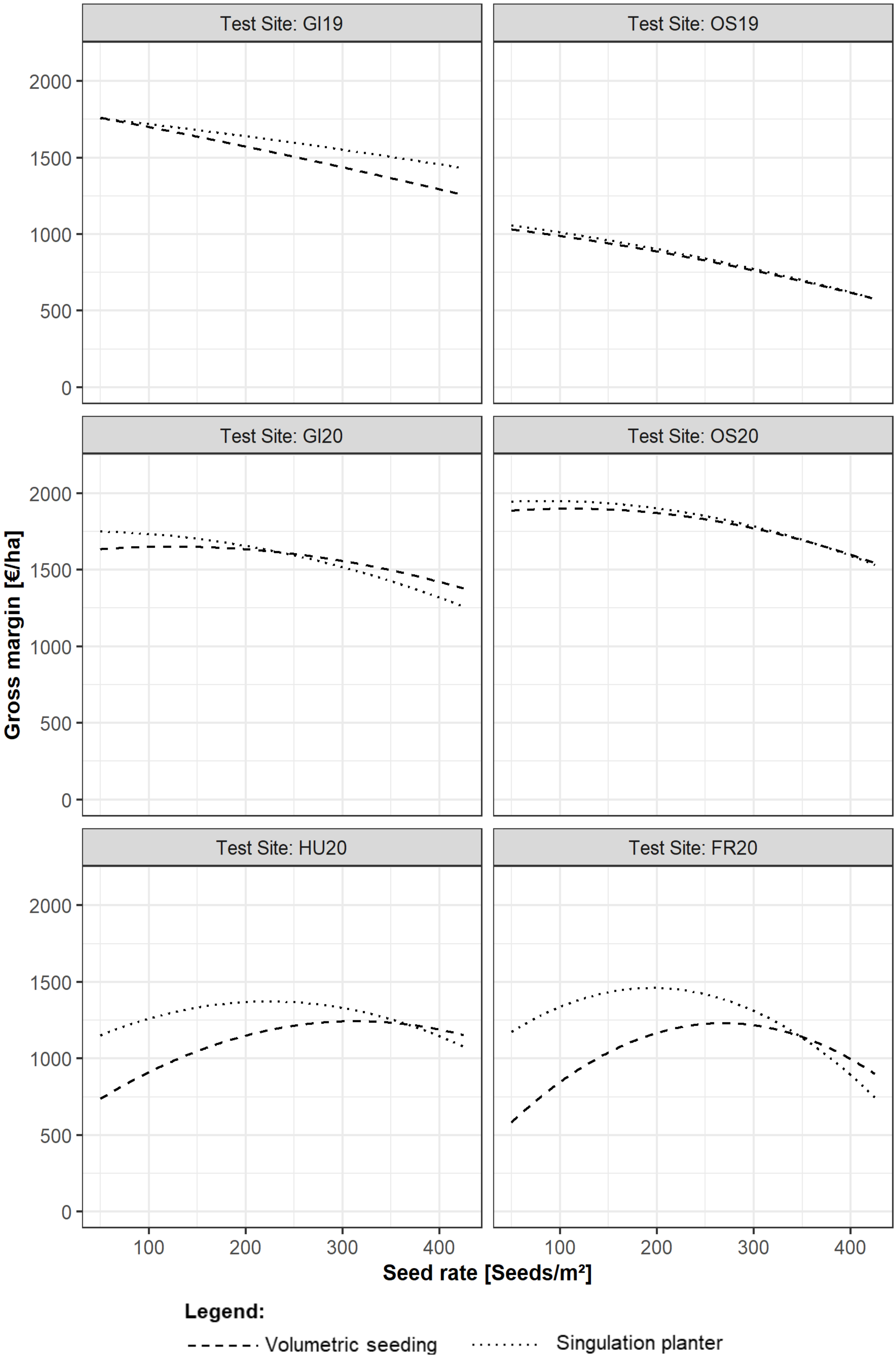

Figure 23: Economic response (gross margin) of winter wheat yield in terms of market price and seed costs of variety hybrid for Test Site, depending on seed rate and technique.

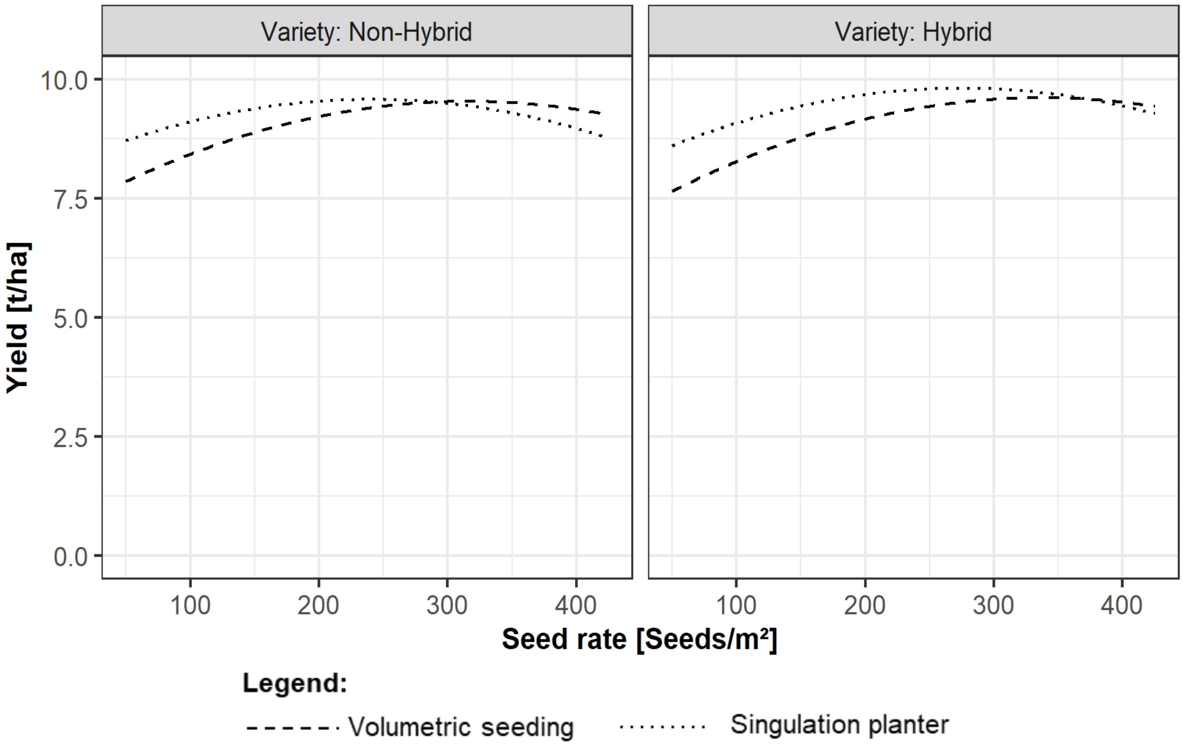

Figure 24: Average agronomic winter wheat yield response for variety hybrid and non-hybrid for all test data depending on seed rate and technique, merged for all test data.

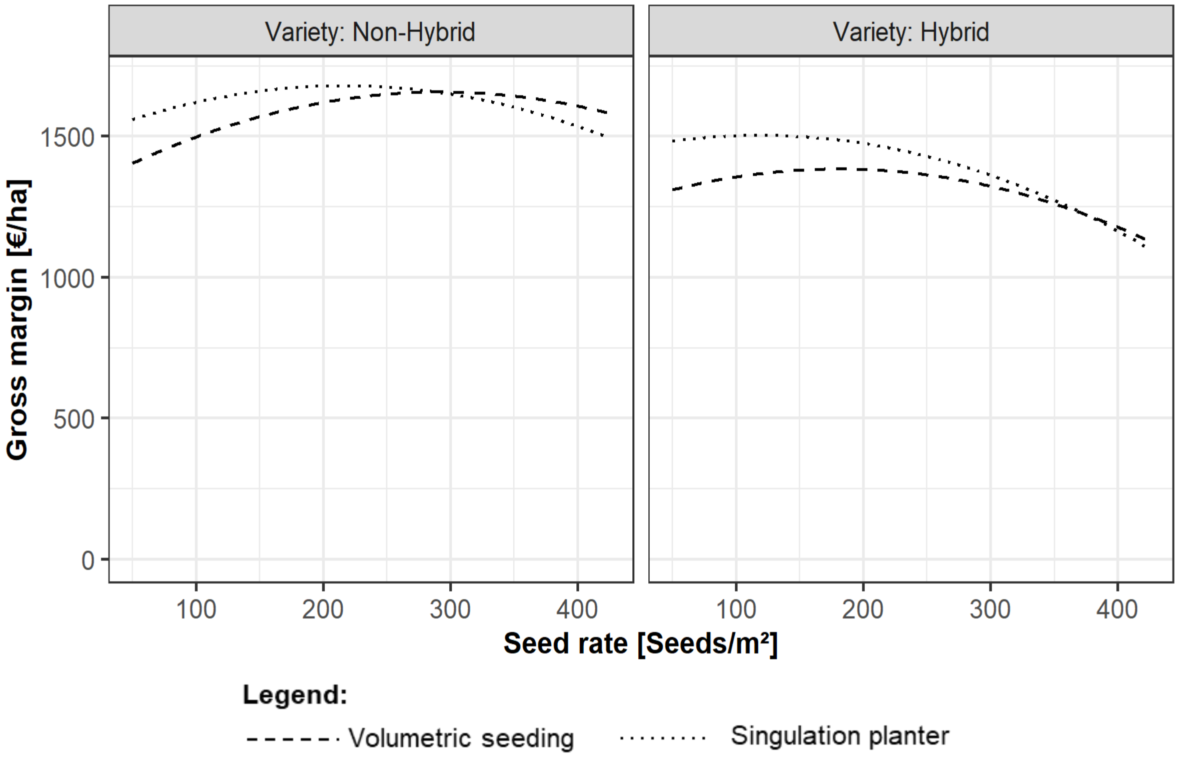

Figure 25: Average economic response (gross margin) of winter wheat yield response for variety hybrid and non-hybrid depending on seed rate and technique, merged for all test data.

Table 25: Agronomic and economic optimum seed rate, corresponding yield and gross marging depending on technique, variety and Test Site. Gross margin reflects wheat yield, market price of 180 €/t and seed costs for non-hybrid (0.20 €/10,000 seeds per ha) and for hybrid (1.32 €/10,000 seeds per ha).

			Agronomic optimum			Economic optimum		
			Seed rate	**Yield**	**Gross margin**	**Seed rate**	**Yield**	**Gross margin**
	Test Site	**Technique**	[Seeds/m²]	[t/ha]	[€/ha]	[Seeds/m²]	[t/ha]	[€/ha]
Variety: Hybrid	GI19	VS	231	10.23	1531	< 50	10.15	1761
		SP	400	11.07	1456	< 50	10.12	1755
	GI20	VS	346	10.92	1502	125	10.10	1651
		SP	243	10.72	1604	< 50	10.09	1750
	OS19	VS	298	6.47	766	< 50	6.10	1030
		SP	268	6.53	818	< 50	6.24	1057
	OS20	VS	298	12.07	1774	111	11.38	1899
		SP	272	12.15	1824	85	11.46	1949
	FR20	VS	318	9.02	1198	269	8.84	1231
		SP	245	9.75	1427	195	9.57	1460
	HU20	VS	406	9.59	1182	314	9.24	1244
		SP	316	9.63	1311	224	9.29	1372
	Mean	VS	337	9.62	1279	181	9.03	1384
		SP	275	9.82	1398	119	9.23	1503
Variety: Non-hybrid	GI19	VS	> 400	11.61	2009	> 400	11.61	2009
		SP	125	10.92	1941	< 50	10.91	1953
	GI20	VS	345	10.13	1754	312	10.11	1757
		SP	171	10.60	1875	138	10.59	1878
	OS19	VS	238	6.50	1123	147	6.45	1132
		SP	218	6.69	1160	127	6.64	1169
	OS20	VS	297	12.03	2105	269	12.01	2108
		SP	277	11.62	2035	250	11.60	2038
	FR20	VS	275	8.75	1520	268	8.75	1521
		SP	238	9.57	1675	231	9.56	1675
	HU20	VS	335	8.90	1535	321	8.89	1536
		SP	281	8.67	1504	267	8.66	1505
	Mean	VS	316	9.54	1654	293	9.53	1657
		SP	240	9.58	1677	217	9.57	1679

4.5.2 Seed singulation value proposition

The previous yield curves and the results of the agronomic and economic optimum calculation have shown already that the use of technique singulation planter produce mostly higher yields. However, the negative interaction of singulation planter to seed rate indicates that the yield benefit of the planter is getting lower with higher rates. Because of that, intersections of yield curves for both used seeding techniques can be detected in the graphs (Figure 20-25).

The extraction of the intersection and the corresponding seed rate visualize the threshold until the singulation planter is producing in minimum the same yield (Table 26). This reaction can be seen for all Test Sites and variety specific yield curves instead of variety hybrid in GI19 and variety non-hybrid in OS20. These observations fits to the individual regression parameters as the singulation planter is mostly positive correlated to yield while having a negative effect on yield when interacting with seed rate (Table 23 and 24).

In GI19, the positive regression coefficient of technique singulation planter to wheat variety non-hybrid (1.241) shifts the curve into a higher yield zone and consequently resulting in higher yields at lower seed densities compared to hybrid. For that reason, the singulation planter produces higher yields compared to volumetric seeding when exceeding the seed rate intersection of 61 seeds/m² when using wheat variety non-hybrid.

In OS20, variety non-hybrid and its interaction to the singulation planter and seed rate is negative correlated und thus indicating that the singulation planter did not generate a higher yield for non-hybrid. Accordingly, no intersection can be detected within the tested range.

Depending on the Test Sites, technique singulation planter generates a higher yield production than volumetric seeding for non-hybrid wheat below a range of 224–400 seeds/m² and for hybrid wheat below a range of 236–400 seeds/m².

Averaged over the Test Sites, the positive yield benefit for technique singulation planter is given for hybrid wheat up to 375 seeds/m² and non-hybrid wheat up to 290 seeds/m² (Table 26). As the singulation planter mostly produces higher yields, the potential seed rate yield ratio has been verified where yield of singulation planter does not fall below the maximum yield value of volumetric seeding. The differing reaction between the Test Sites and in addition the difference between agronomic and economic seed rate threshold can be seen in the visualization (Figure 26).

While the maximum yield level of volumetric seeding exceeds the maximum yield of the planter, no bars are indicated for variety non-hybrid in GI19, HU20 and OS20. In contrary, a larger spread is given for non-hybrid at the other Test Sites. With the singulation planter, yield production can be in minimum maintained between 50-339 seeds/m² in GI20, 50-393 seeds/m² in OS19 and 134-342 seeds/m² in FR20 when using non-hybrid wheat. The impact on seed rate range stays mostly unaffected when going for the maximum economic return. Only in OS19, this range is reduced by 81 seeds/m² less at the upper end.

Table 26: Yield curve intersection of technique volumetric seeding (VS) and technique singulation planter (SP) for variety and Test Site.

	Intersection yield curve of technique VS & SP		
	Test Site	Seed rate with same yield [Seeds/m²]	Note:*
Variety: Hybrid	GI19	61	1
	GI20	236	2
	OS19	> 400	2
	OS20	365	2
	FR20	348	2
	HU20	367	2
	Avg. of Test Sites	375	2
Variety: Non-hybrid	GI19	224	2
	GI20	339	2
	OS19	> 400	2
	OS20	< 50	3
	FR20	404	2
	HU20	256	2
	Avg. Of Test Sites	290	2

*Note: 1 Singulation planter performs better above this rate
2 Singulation planter performs better below this rate
3 Singulation planter has no better performance within testet range

Comparing the average curve above all Test Sites, singulation planter maintains the yield level for non-hybrid between 199-282 seeds/m², while the economic level can be maintained in a larger range of 145-290 seeds/m².

Focusing on hybrid wheat, an enlarged deviation of the seed rate ratio, where the singulation planter maintains the highest yield and economic return can be seen. Interestingly, the maximum yield of volumetric seeding can be maintained with the singulation planter in a large range in GI19 (80-400 seeds/m²), but not for the economic return. In contrary, maximum yield of volumetric seeding cannot be maintained in GI20, therefor the economic return can be maintained in a range of 50-205 seeds/m² when using the singulation planter. By fact, the hybrid wheat yield production still increases with higher seed rates in GI19 when using the singulation planter and in GI20 when using volumetric seeding (Figure 21). As a consequence, the increased hybrid wheat seed costs do not leverage the small yield increase at higher seed rates.

Apart from that, the maximum yield level of volumetric seeding can be maintained for hybrid wheat at the other Test Sites. In HU20, seed rates can be slightly reduced down to 281 seeds/m², much lower seed rates while maintaining the yield can be induced in OS20 (207 seeds/m²), OS19 (167 seeds/m²) and FR20 (146 seeds/m²).

To maintain the maximum economic return of volumetric seed metering for hybrid wheat, the seed rates can be reduced by use of singulation planter down to 50 seeds/m² in GI20, OS19 and OS20. However, highly differing ranges can be seen here as well. While the

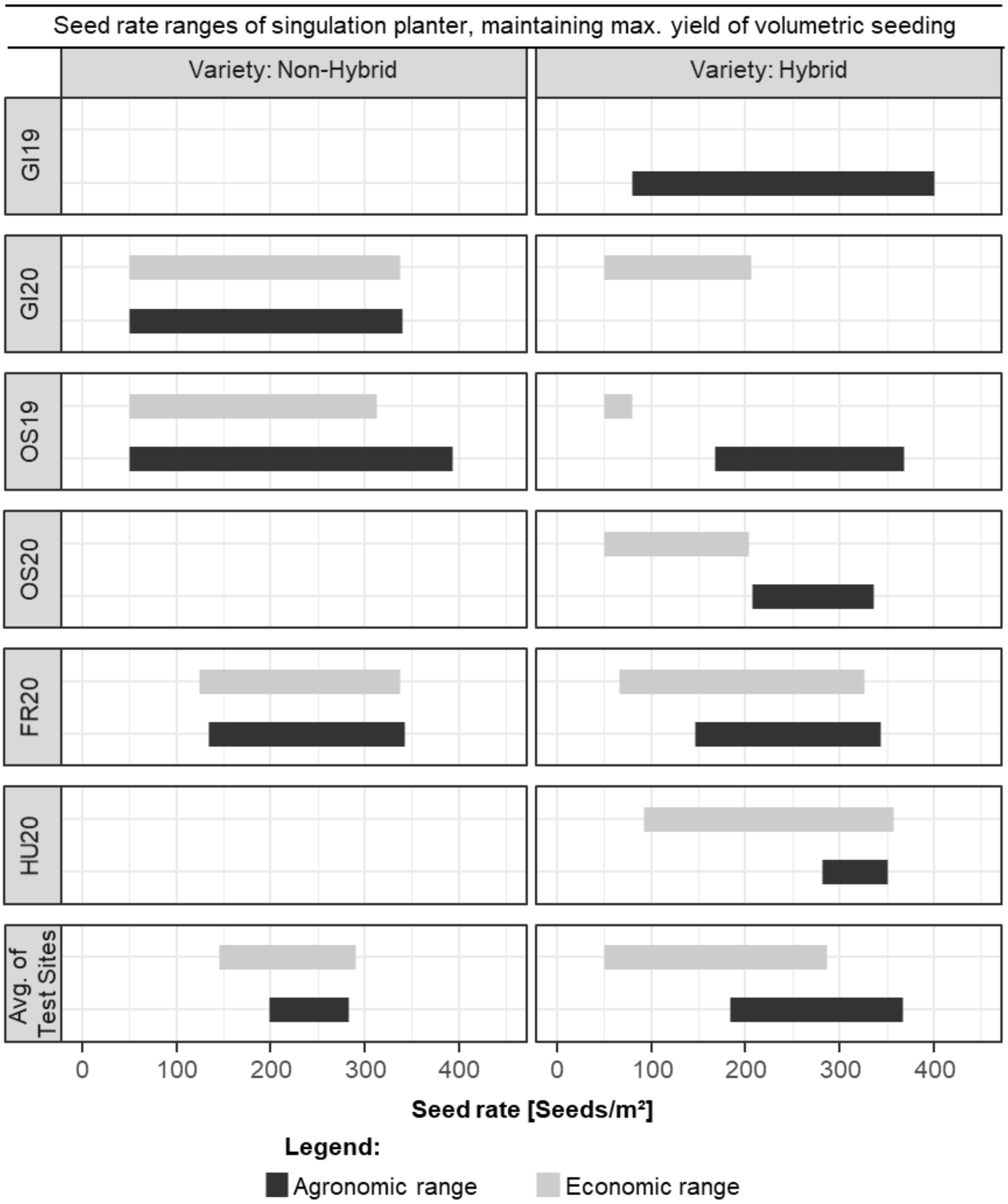

Figure 26: Seed rate range where use of technique singulation planter (SP) maintains in minimum the max. yield/gross margin of technique volumetric seeding (VS) for variety, Test Site and all Test Site data merged. No bars indicate no opportunity for technique SP to maintain max. yield/gross margin of VS.

economic return can be maintained in OS19 only in a range of 50-79 seeds/m², a larger range is given in OS20 from 50-203 seeds/m² and in GI20 from 50-205 seeds/m². Having a much larger ratio in FR20 (65-326 seeds/m²) and HU20 (91-357 seeds/m²), a higher opportunity is given to maintain the economic return for hybrid wheat when using the singulation planter.

Over all data, technique singulation planter maintains yield production and economic return compared to maximum levels of volumetric seeding for both varieties. For non-hybrid wheat, yield level can be maintained down to 198 seeds/m² and economic return down to 145 seeds/m². Higher seed rate reductions are possible for hybrid wheat with 183 seeds/m² when maintaining yield and down to 50 seeds/m² when maintaining economic return.

5. Discussion

Within farming processes, seeding is one of the elementary processes that is influencing crop growth and yield production [30]. As foundation for the upcoming growing period an equal crop establishment and optimum plant density can be guaranteed by the seeding operation. Failures during seeding can increase the production risk due to unproductive or weak crops and a higher potential for lodging and crop diseases [95]. Besides an optimum plant density, individual plant room spacings are agronomic beneficial as they reduce the intraspecific competition of the single plants [40, 59]. Especially during early development of wheat, a homogenous spatial plant distribution is important [64].

After field emergence, the differing plant space distribution quality in trench of the used seeding techniques was obvious, especially at the low seed rates of 80 seeds/m² (Figure 27).

Figure 27: Winter wheat field emergence at 80 seeds/m², comparing plant distribution quality of volumetric seeding (left) and singulation planter (right). Oschersleben, 2019.

Volumetric seed metering is not able to realize equal seed spacings in trench [40, 61]. On the one side, the volume-based dosage when using cell wheels is not able to dose single seeds, on the other side several factors during seed transport from cell wheel to seeding discs impact the seed distribution as seeds are jumping in tubes and are randomly distributed when using pneumatic seed distribution systems [3, 28, 33]. Using the CoV of seed spacings as indication for seed spacing accuracy, values between 90-110 % are typically mentioned when using volumetric seed metering [30, 31, 78]. These values fit also to the average CoV of the in field trial used reference for volumetric seeding.

Improved seed spacing accuracy in trench can be realized when using a singulation planter, as seeds are individually picked up by the singulation discs [29]. Tests with canola have proven already CoV reductions down to 50 % when using a singulation planter instead of volumetric seed distribution [30, 31]. The own results with winter wheat seeds showed that a similar CoV was only realized with the singulation planter at a low rate of 80 Seeds/m². As in the study with canola a density of 60 seeds/m² was tested, these values are mostly comparable. However, the CoV of the singulation planter is increasing when seed rates are getting higher. A similar response for wheat seeds was indicated in the study of MÜLLE & HEEGE (1980). While testing different seed frequencies on a singulation planter, they detected an 8 % increase of CoV when

increasing the seed frequencies from 20-60 seeds/sec [76]. Referring to the own data, CoV is increased in average by 22 % at comparable seed frequencies between lowest to highest seed densities (15-59 seeds/sec). The larger difference compared to MÜLLE & HEEGE (1980) might base on the evaluation method, as they evaluated in laboratory the seed distances on a lime stripe whereas the own data are based on emerged plants in field. Increased variability in spacing quality under field conditions can be expected as seeds might not emerge and/or the seed position is influenced by soil roughness. For that reason KACHMAN & SMITH (1995) stated: "*Much of the variability in spacing could be removed by evaluating planters under laboratory conditions. However, field trials are also needed to accurately evaluate how a planter will perform in field*." [49].
Besides seed rate as influencing parameter on seed frequencies, an additional dependency is determined by driving speed. For that reason it is becoming more challenging to realize a good seed spacing quality, when driving speeds will increase [54, 100].
The increased CoV at higher seed densities is also a mathematical issue. At higher densities, the mean seed or plant distance is decreasing. As the CoV is calculated by dividing standard deviation by mean distance, the lower mean distance at higher seed rates has more impact. In fact, a deviation of 1 cm in plant distances can be easily reached if the seedling is emerging on the left or right side of the grain. It is approximated that this impacts the CoV by 9.4 % at 7.5 cm mean plant distances and by 37.8 % at 1.9 cm mean plant distance, if 20 % of the measured plant distances deviate by 1 cm [12].
In contrast to CoV, the visualization of plant distances in a histogram delivers additional insights about the frequency of plant distances in field. Typically, the histogram of volumetric seed metering follows an exponential function while the histogram of a singulation planter follows a normal distribution around the mean distance [30, 31, 33, 40, 49]. Referring to the histograms of the evaluated field data, the previous statements can be mostly agreed, despite the curves of the singulation planter at seed rates of 240 seeds/m² and above. These curves are more likely an exponential function, tending to have a peak around the mean distance. When implementing the appropriate method of grouping the seed distances into multiples, skips and the target range [44, 49], the shift from normal distribution towards exponential function can be also indicated, as the advantage of hitting the target distance when using the singulation planter is reduced from 35.2 % to 7.5 % between lowest and highest seed density.

To sum up, the longitudinal seed distribution can be improved when using a singulation planter. The lower CoV's and the reduction of multiple and missing seeds indicate the significant improved seed spacing quality of the singulation planter, in particular for the lower seed densities. With that, hypothesis 1 is approved, declaring that the use of a singulation planter is significantly improving the longitudinal plant space distribution quality compared to volumetric, random seed metering.

Considering that the performance and accuracy of the singulation planter is going to be reduced at higher seed frequencies, it is still a challenge to maintain the singulation quality at high seed densities and/or higher driving speeds [54, 76, 100]. Even though an equal longitudinal seed distribution is agronomic beneficial and several investigations were spend to improve seed spacing quality, no suitable technical solution has been successfully brought into market yet [53].

5.1 Crop establishment

After seeding, seed germination is the first important step in crop establishment [95, 107]. Key influencers are soil water content, temperature and the gas exchange of oxygen in soil [56]. Referring to these three parameters, the differences in emergence rate between the Test Sites can be explained. Abnormal dry conditions before seeding and additionally no rain directly after seeding in OS19 and HU20 resulted in dry soils and missing soil water, resulting in a later and additionally lower emergence rate. In contrary, wet soil conditions, intense rainfalls, and low temperatures after seeding in FR20 resulted in a slow and reduced emergence as well. Due to seeding into wet soil and the following rain, the soil surface was muddied. Combined with the over saturated soil water content, it can be assumed that the soil gas exchange was impacted and thus affecting the lower emergence rate [37].

However, sufficient soil moisture is still the most important parameter for seed emergence. When the water availability is limited, seeds need to compete for soil water after seeding. As result, a poor seed distribution quality can affect an inefficient resource utilization [54], resulting in a reduced seed emergence. This effect is well known for corn and sugar beets and also reported for canola, as an uneven seed distribution constrains water and nutrient supply [30, 33]. Based on the research of GRIEPENTROG (1995), seeds are competing already during germination, resulting in reduced root development. If the availability of soil water is not sufficient, the seedlings might not emerge [30]. Despite an improved seed spacing quality when using the singulation planter, a higher emergence rate was only reported in HU20 and FR20. Due to the dry conditions in HU20 before and after seeding, the 16.4 % higher emergence rate when using the singulation planter can be explained as the improved seed placement reduced the competition for the limited soil water availability. In contrary, this explanation doesn't fit to FR20 as the soils were water saturated. It needs to be questioned, if the different seed opener of both used seeding techniques might impacted the seed placement under the wet soil conditions.

While the improved seed spacing quality of the singulation planter has potential to increase the emergence rate, technical sensitivity of a planting system can also reduce the applied target rates. Due to the usage of a pneumatic singulation system, changes in vacuum pressure, turning speed of the singulation disc (driven by seed rate and forward speed) and usage of separators for double seed elimination are expected to impact the single seed output. Even under perfect machine settings, a single seed output of 96 % in wheat is reported [76]. Due to the sufficient water availability for emergence within both test years in Giessen and Oschersleben, the lower emergence rate of the planter can be explained by these effects.

The reaction of the tested varieties on seed emergence can be referred to the differing seed sizes between hybrid and non-hybrid seeds. The hybrid wheat had larger seeds compared to non-hybrid, which was also indicated by the grain weight (TKW: Hybrid = 46 g; Non-hybrid = 39 g). On the one side, larger seeds need more water for germination which can limit the emerging performance at marginal soil water contents [4, 42, 106, 107], on the other side the singulation system of the planter can react differently between small and large grain sizes and also grain forms, as the hole diameter for picking up the seeds might not fit to differing seed sizes [76]. This also explains the trend of the lower emergence rate of the hybrid wheat seeds, when seeded with the singulation planter.

Besides seed placement quality, the early intraspecific competition on seed germination is driven by seed rate. Greater plant losses at higher seed densities can be expected as seedling mortality and environmentally stresses are increased [91]. In accordance to SPINK et al. (2000) & WHALEY et al. (2000), the deviation of plant density to seed rate is increasing at higher seed densities [91, 103]. Also, additional significant plant losses at higher seed rates and thus plant densities were seen after winter. A comparable response was found by HOLEN et al. (2001), with an additional differing response due to the tested cultivars, as they varied in winter hardiness [42]. This is on the one side nutrition based, because less plants accumulate soil resources more efficiently [7], resulting in higher contents of nitrogen and potassium within the single plants, increasing the frost resistance [102]. On the other side, crop growth reacts to the increased plant competition resulting in faster crop elongation due to the shade avoidance strategy [97]. As consequence, the reproductive apices are more exposed to frost and thus increasing the susceptibility to frost damage [102]. Lower temperatures, wind exposure and missing snow cover increase the risk of plant desiccation and thus plant death [42]. This also explains the slightly higher plant losses in GI19, as the average temperature was from December to February 0.7-1.5 °C lower compared to OS19.

When growing winter wheat, optimum plant densities are stated between 62-225 plants/m², depending on yield environment and time for seeding [7, 27, 42, 91, 93, 103]. It is an interesting fact, that high seed densities tend to reduce their plant densities towards the optimum plant densities. As supplementary result of early competition during seed germination and increased frost susceptibility, the outcoming spring plant density at 320 seeds/m² is decreased to 171 plants/m² in GI19 and 184 plants/m². As the winter losses were evaluated only in the first test year, this finding needs to be treated with care.

All in all, the crop establishment after seeding is mostly determined by seed density. As the seeds need to compete for soil resources and growth space beginning with seed germination, the ratio of applied seeds versus plants starting into spring vegetation is increasing when seed rates increase.

Although there is potential for higher emergence rates when using a singulation planter, the technical sensitivity of a planter system in terms of producing lower single seed output in contrast to target rate, tends to leverage the positive effect on seed emergence.

5.2 Crop development

Due to the improved plant distribution when using the singulation planter, a higher tiller rate was expected as there is less competition between the plants. This effect was verified due to significantly more tillers per plant when using the singulation planter, but the tiller production per area did not differ between both used seeding techniques.

Generally, winter wheat plants adapt the crop development in terms of neighboring plants (Figure 28). If there is still growth space available, wheat plants react with profuse tillering to use this space more efficiently [97]. For that reason, tillering is the main compensatory mechanism at low plant densities [27]. When using the singulation planter, plant density was slightly lower, indicating the dependency on the plant density, which has been also proven by the regression model, declaring the significant effect of plant density to number of tillers per plant (Table 13).

No more substantial increase in tillers per area was found at seed rates above 160 seeds/m², which is indicating the self-regulation due to the intraspecific competition [95]. The ability of producing tillers highly depends on captured sun light. Influencing parameter is the R:FR ratio which declines due to shading. As result of higher plant densities, shading is increasing while the R:FR ratio declines. Using these signals, plants stop tillering if the R:FR falls below the threshold value of 0.25-0.3 [1, 21, 103].

Figure 28: Seed rate specific reaction of a single winter wheat plant on tiller production, comparing 80 seeds/m² with 9 tillers (right) and 240 seeds/m² with 5 tillers (left). Waldems, 2020.

While not all tillers produce an ear bearing stem, the number of unproductive tillers is also of interest. The tiller reduction is significantly determined by seed rate and increases at higher densities. At low plant densities, single plants can use soil resources more efficiently and the potential of capturing radiation is increased as plants are less shaded by other plants [103]. Therefore, tiller survival is increased at lower plant densities [92]. Compared to the lowest tested seed rate of 80 seeds/m², 110-160 more unproductive tillers/m² are produced when increasing the rates up to 320 seeds/m². This is also of importance, while each unproductive tiller causes a waste of soil resources and just small parts of nutrients and carbohydrates can be retransferred into the ear bearing stems [16, 103]. If there are limitations in crop nutrient supply at later growth stages, impact on yield production can be expected.

While the singulation planter is not affecting the tiller density of wheat, the opposite effect was detected for ear density, indicating a potential effect of the improved seed spacing quality. KOTTMAN et al. (2019) found also a significant higher ear density when wheat plants are spaced in uniform patterns [54], which is theoretically proofing the own finding. However, the own result needs to be treated with care as large impact is driven by the Test Site FR20. Here, the singulation planter produced in average 149 ears/m² more while no significant difference in ear density was indicated for the other Test Sites. When excluding Test Site FR20, no differences in ear density between singulated and volumetric seeding were found for the own results. Based on the significant quadratic regression, ear density mostly depends on plant density and is thus affected by seed rate. This is also proven when comparing the number of ears per plant as they are not any more significantly differing in FR20.

Besides light as determining factor for tillering and tiller survival, these processes are also determined by water and nutrient supply and thus important for final ear density [7, 91, 103]. Time of seeding drives tiller and ear formation too, as late seeding reduces the vegetative time of the plants to produce tillers for space compensation [7, 91]

This knowledge can be transferred to the differing ear densities of the Test Sites. The lower ear density in HU20 is a result of missing rainfall in winter and spring, in GI20 due to a delayed nitrogen application causing a lag of nutrients during early development in spring and in FR20 caused by late seeding and slowed crop development in November due to oversaturated soil water. In GI19 and OS19 optimum growing conditions produced a typical ear density of 500 ears/m². The highest ear density in OS20 might be an effect of above average temperatures during winter, effecting a longer period for crop development. Also, water supply was sufficient during winter and soil water potential seemed to be filled up to compensate the dry periods in April and May.

Although both tested wheat varieties have the same classification for ear development, hybrid wheat produced slightly lower ear densities compared to non-hybrid wheat. However, the tendency of slightly lower emergence rates in combination with a slightly reduced number of ears per plant compared to non-hybrid confirms that hybrid wheat is not able to produce higher ear densities. PREY at al. (2018) claimed also a 4.1 % lower ear density of hybrid wheat compared to non-hybrid wheat. Interestingly, their results show that heterosis of ear development is mostly associated in a negative trait [84].

To conclude, winter wheat can compensate potential growth space area through tiller and ear production. This process is mostly driven by seed rate and consequently plant density in field, as the single plants detect the presence of competing neighbors through changes in accumulated sun radiation. Also, environmental conditions influence the compensatory mechanism as sufficient water, nutrients, sun light and growing time is required to fulfill an acceptable ear density in field. Nevertheless, it is interesting that against the opinion of seed breeders hybrid wheat produces lower ear densities. Despite the fact, that an improved plant distribution increases the single plant efficiency cause of reduced intraspecific competition, no impact on tiller and ear density was found.

5.3 Grain yield formation

With regard to Hypothesis 2, a more homogenous plant distribution when using the singulation planter significantly increases yield by 5.4 % in average. In an agronomic perspective, this yield increase is the result of reduced intraspecific plant competition and maximized area use efficiency, resulting in less self-shading, improved light interception and light use efficiency and less resource competition with neighboring plants [7, 47, 54, 100]. These aspects can also be important in terms of water usage, because more uniform spaced crops have a lower water consumption [92]. In case of insufficient water supply during grain filling, more soil water can be a driver for higher grain weights. Because of these aspects, a more homogenous seed spacing quality enhances the crop plant performance with expectation of higher wheat yields [33, 54]. However, the effects on wheat yield when improving seed spacing uniformity are rarely analyzed and the effects vary. While TAO et al. (2019) verified 6-21 % yield increase in wheat at uniform planting compared to drill seeding [92], KOTTMAN et al. (2019) reported no significant yield response at uniform planted winter wheat [54]. Referring to their research it needs to be mentioned, that the uniform planted wheat was only tested at a density of 150 seeds/m² compared to drill seeded plots with 150 and 350 seeds/m². Despite no significant differences in yield production, slightly lower yields can be seen when 150 seeds/m² were drill seeded, while 150 seeds/m² uniform planted generated the same yield then 350 seeds/m² drill seeded [54]. These findings are comparable with the own results that declare no significant yield loss down to 160 seeds/m² when using the singulation planter compared to 320 seeds/m² volumetric drilled (Table 18).

As the use of volumetric seed drills and seed rates above 300 seeds/m² reflect the typical applied farming practice when seeding cereals and in particular winter wheat, seed rates can be reduced in average by 50 % while maintaining the yield when using a singulation planter. Nonetheless, the potential seed rate reduction while maintaining the yield differs between the

Test Sites, resulting in potential reductions down to 80 seeds/m² in GI19 and GI20 up to a maximum reduction to 240 seeds/m² in OS20 and HU20. All in all, this also supports the third hypothesis, that winter wheat yield can be maintained at lower seed densities when using a singulation planter.

Anyway, winter wheat yield and the effect of improved crop space homogeneity due to singulation is highly impacted by the environmental conditions of the Test Sites. In HU20 and OS20, intense rain falls during grain filling process provided the needed water supply for an above average yield response at these Test Sites. While this has not impacted the singulation yield response in OS20, more than 10 % higher wheat yield was found in HU20 when using the singulation planter. Due to below average rainfall in HU20 lasting from seeding into early summer, the yield effect of the singulation planter was driven by the improved emergence rate and the higher ear density compared to volumetric seeding. Because of the water limitations, the compensation of plant growth space is limited resulting in less tillering and lower ear densities. For this reason, the recommendations for the optimum plant density are higher when wheat is grown under resource limited conditions [7, 60], which has also been seen in the 30 % lower yield between highest and lowest seed rate in HU20. While in OS20 no water limitations were given during the important growth stages of tillering, ear production and grain filling, the effect of improved plant placement was leveraged. The 7 % yield difference between lowest to highest seed rate also indicates that enough water resources were available for producing tillers and the for yield production important high number of ears/m².

A delayed nitrogen availability in GI20 reduced the tiller and ear production but with no difference between both used seeding techniques. Nonetheless a 5 % yield increase when using the singulation planter declares an impact on the yield parameters, that are compensated by a significant higher grain production per ear. While there is also a competition for resources between stem and ear development, ear size and thus grain number per ear is determined by tillering [34]. As result, the singulated wheat plants used at the same tiller rate the limited nitrogen resource more efficiently with consequently more grains per ear. Despite the lower ear density in GI20, the growing conditions were still good enough for the low seed densities to compensate growth space, resulting in average 4.8 % lower yield between lowest to highest seed density.

The 18 % higher yield for the planter usage in FR20 is mostly the result of a 25 % higher plant emergence and thus a higher plant density. This caused also a significant higher ear density which is additionally explaining the yield increase, as ear density is one of the main factors to improve the yield response [7]. Late seeding and a poor crop development in FR20 before winter reduced the compensation potential of the wheat plants for the lower plant densities, as result of less time for accumulating thermal time for full vernalization [91]. This reduced yield by 26 % when reducing seed rate from 320 seeds/m² down to 80 seeds/m². Taking that into account, a later seeding date requires higher plant densities to guarantee a high yield production [7, 17, 91].

The importance of water availability for grain yield formation was identified in GI19 and OS19. While the ear density did not differ between both Test Sites, a lower amount of rain in OS19 reduced grain weight and grain number per ear compared to GI19 and thus causing ~4 t/ha lower yield in OS19. The dry conditions in OS19 caused a higher resource competition between tillering and ear development, resulting in lower grain number per ear [34]. Additionally, the limited assimilate supply during grain filling affected a lower grain weight [23]. While grain weight is mostly influenced by variety and environmental conditions [60], ear density and grain number per ear are mentioned as the key driver for yield production [7, 34]. However, wheat grain yield is generally determined by ear density, grains per ear and grain weight [15, 17], which is also proven by the own regression (Table 21). Using this as indicator for the influenced components when singulating wheat, this also proves that an improved plant distribution can increase yield by a higher ear density in FR20 and HU20, while the yield response is derived due to more grains per ear and in some cases higher grain weight in GI19, GI20, OS19 and OS20.

Hybrid wheat is generally characterized by a higher and more stable yield production compared to non-hybrid wheat [52, 63, 75, 98]. This is on the one side a result of heterosis in root development, effecting an improved buffering capability of water and nutrients if limited and on the other side the heterosis of increased biomass production which is improving the radiation use efficiency and thus the assimilate production within the hybrid wheat plants [52, 84, 90, 98]. The yield response of hybrid wheat is mostly declared between 5-10 % [35, 62, 63, 84, 89], in contrary no clear yield response was recognized for hybrid wheat in the own research, as slightly higher and lower yields for hybrid wheat, differing between the Test Sites, delivered in average no yield advantage. In that point of view, hypothesis 4 is refuted as the yield increase of hybrid wheat was not detected. Further affirming, PREY et al. (2018) recognized a comparable response of slightly lower ear densities, lower grain weights and more grains per ear for hybrid wheat [84]. Agreeing to PREY et al. (2018), the response of hybrid wheat can depend on the agronomic management with respect to seed rate and nitrogen fertilization, that needs to be considered for further research investigations. 76

Due to higher seed costs of hybrid wheat, lower seed densities between 120-150 seeds/m² are recommended, as higher seed densities reduce the economic threshold [85, 86]. The yield difference between volumetric and singulated seeding is higher at these lower seed densities, so the usage of a singulation planter can be more profitable as the seeds will be more evenly distributed resulting in a more efficient plant growth which is finally enhancing yield production compared to volumetric seeding.

Grain protein content is negative correlated with yield production (Figure 19). Cause of the trend of higher yields when increasing seed density or using a singulation planter, protein content is decreasing. TAO et al. (2019) also found a trend of lower grain protein content when wheat seeds were planted in uniform patterns. Nevertheless it was mentioned that the higher yield production of uniform planting increased the total protein removal which is also indicating a higher nitrogen accumulation and thus a higher nitrogen use efficiency [92]. However, grain protein content is more important for further marketing and usage of harvested wheat, as a threshold of 12 % is mostly used to distinguish if the grains are good enough for baking quality, resulting also in a higher offer of the wheat price. As the singulation planter and thus an enhanced plant space uniformity tends to decrease the grain protein content, an adapted nitrogen fertilization in terms of rate and timing of application can make sense to guarantee a higher grain protein content.

All in all, the more homogenous plant distribution when using a singulation planter can increase yield production on the one side and maintain yield levels at lower seed densities on the other side compared to volumetric seeding. Depending on the environmental conditions, the yield increase can be contributed to a better crop emergence and thus ear density or to a higher number of grains per ear. Also, the for economic reasons recommended low seed densities of hybrid wheat can increase the need for a technical solution that singulate and more evenly distribute wheat seeds in field as the seed distribution quality of a volumetric seed metering system is not good enough to fulfill an efficient plant area usage. Finally, higher protein removals when using the singulation planter indicate a higher nutrient efficiency which can deliver additional potential in areas that are restricted in the usage of nitrogen, as the combination of improved seed spacing quality and adapted fertilization strategy can help to still generate high grain qualities.

Taking these facts into account, a redefinition of the optimum winter wheat seed rate when wheat plants are more uniformly spaced might help to simplify the development of a new singulation concept for small grain seeding. The approach of using Voronoi polygons was mentioned already as advanced method to identify the distribution quality of individual plant growth area and to predict yield production through estimating the single plant yield (chapter 2.5.3). As this methodology is in contrary to the use of CoV unaffected by row spacing and seed rate [32, 33], it is worthwhile to further investigate research activities on this method in winter wheat. This could generate additional, beneficial insights about the optimum plant density and thus the minimum agronomic threshold for seed rate of winter wheat.

5.4 Seed technique as driver for cost saving and increased economic return

The use of volumetric seed metering in combination with seed densities above 300 seeds/m² is still the common practice when seeding winter wheat. In an agronomic point of view, the estimated, variety specific maximum yield production between 316-337 seeds/m² when using a volumetric seed drill fits to the high seed densities that are typically drilled. Nevertheless, the target seed rates highly depend on the crop establishment before winter and the resource availability for crop space compensation in spring, resulting in potentially +/- 25 % seed rate adjustment.

A similar conclusion is mentioned by LINDSEY et al. (2020), as years with poor growing conditions can affect a risk of lower yields if seed densities are too low [58]. They estimated also the agronomic and economic optimum seed rate but indicating higher seed rate ranges of 346-476 seeds/m² for the agronomic optimum and 241-386 seeds/m² for the economic optimum seed rate. Comparing the tested seed rates that were used as input for estimating the optimum density, higher rates from 185-618 seeds/m² were used in the research of LINDSEY et al. (2020), while the own research reflected data in a range of 80-320 seeds/m². However, a similar trend and dependency of optimum seed rate to seed costs was indicated.

The linearly increase of seed costs is reducing the agronomic optimum density to a lower, economic optimum seed rate. While the economic optimum rate for non-hybrid wheat is 7-10 % lower compared to agronomic optimum, the more than 4 times higher seed costs for hybrid wheat reduce the economic optimum seed rate by 46-56 % in average and demonstrate that seed rate can be a decisive factor if seed costs are more expensive and thus diminish potential yield advantage of hybrid wheat [35, 52, 63]. This corresponds also to the general statements that it is inevitable to reduce seed densities of hybrid wheat seeds to achieve the maximum economic return [52], which is also mentioned by seed breeders, declaring an economic threshold for hybrid wheat seeds when exceeding 150 seeds/m² [85, 86]. Nevertheless, the economic optimum seed rate of hybrid wheat is not able to compete against the profitability of non-hybrid wheat [84]. As there was neither in the multivariate yield analysis (Table 17) nor in the regression modelling (Table 24) significant impact of the interaction variety and seed rate, a comparable yield response is indicating that progress on breeding non-hybrid wheat is still able to compete with hybrid wheat performance [84]. Consequently, much higher seed cost savings of hybrid wheat seeds leverage the yield loss when going from agronomic to economic optimum seed rate.

The economic potential of hybrid wheat can be increased by using a singulation planter. As a more uniform plant spacing homogeneity has more capabilities to stabilize yield production at lower seed densities, a higher economic return is reached by the higher yield benefit of the planter at lower seed densities. The additional revenue is in average up to 100 €/ha increased when using a singulation planter in hybrid wheat compared to non-hybrid wheat. This also solidifies hypothesis 5, as the use of a singulation planter generates a higher revenue in hybrid wheat compared to non-hybrid wheat.

However, the cost estimation reflects only seed costs without recognizing potential higher machine and maintenance costs for a singulation planter system. Due to a missing suitable machine concept for singulating cereals, a value needs to be generated that is indicating the potential maximum increase in machine costs of a singulation system per hectare.

As hybrid wheat is still a niche sector with just 1 % of the global wheat production [62, 84, 89], and as additional 10-20 years of breeding efforts are estimated for developing more efficient hybrid wheat varieties with increased return for farmers [35], the higher value proposition of the singulation planter in hybrid wheat won't be the ideal value to classify potential higher machine costs. Consequently, the additional average return of 22 €/ha when using the singulation planter in non-hybrid wheat can be used as threshold for a potential singulation solution concept in small grain seeding, including fixed machine costs plus fixed and variable maintenance costs.

Besides yield increase and seed cost savings, additional logistical cost saving potential can be assumed when using a singulation planter. When going for maximum economic return, 25 % seed rate reduction are possible compared to maximum return of volumetric seeding, or if the maximum economic return of volumetric seed metering should be maintained, up to 50 % lower seed densities are possible when using a singulation planter. Based on the potentially lower seed rates, less seeder refills can increase the seeding productivity per day, also fewer seed transports are required from farm into field.

In addition to that, sustainability value can be generated as a lower amount of wheat seeds reduces the amount of chemical seed treatment needed. Apart from that, lower plant densities are associated to have less disease pressure, reduced risk for lodging and an increased nutrient efficiency [8, 25, 48, 58]. As these parameters were not specifically tested, further research is required, to clarify additional cost saving potentials in plant protection and crop fertilization that will also have sustainability impact.

However, the typically used high seed densities in non-hybrid wheat varieties have less cost impact, ranging between 15-25 % of the overall crop management costs (chapter 2.6). For that reason, higher seed densities are mentioned to be a low-cost insurance to compensate potential plant losses and is also part of an integrated weed management strategy as higher seed densities have larger impact on weed suppression [91, 96]. In contrary, a more uniform seed/plant distribution is generally growing more evenly, resulting in a faster and improved soil coverage, which can be also indicated by higher Leaf-Area-Indices (LAI) [47, 54, 96]. Based on the research of OLSEN (2007), uniform planted patterns of wheat plants at 204 seeds/m² had the same LAI than drill seeded at 449 seeds/m² [47]. This also strengthens the value proposition when using a singulation planter at lower plant densities, as the more even plant distribution and thus soil coverage is affecting weed suppression in a comparable manner than volumetric drilled at high seed densities.

In the own field trial research, no specific evaluation of the LAI was measured. Nevertheless, the improved soil coverage when using the singulation planter was visible in field when comparing the wheat crop growth during stem elongation in spring (Figure 29). While the improved plant spacing quality of the singulation planter ensured an even soil coverage at low

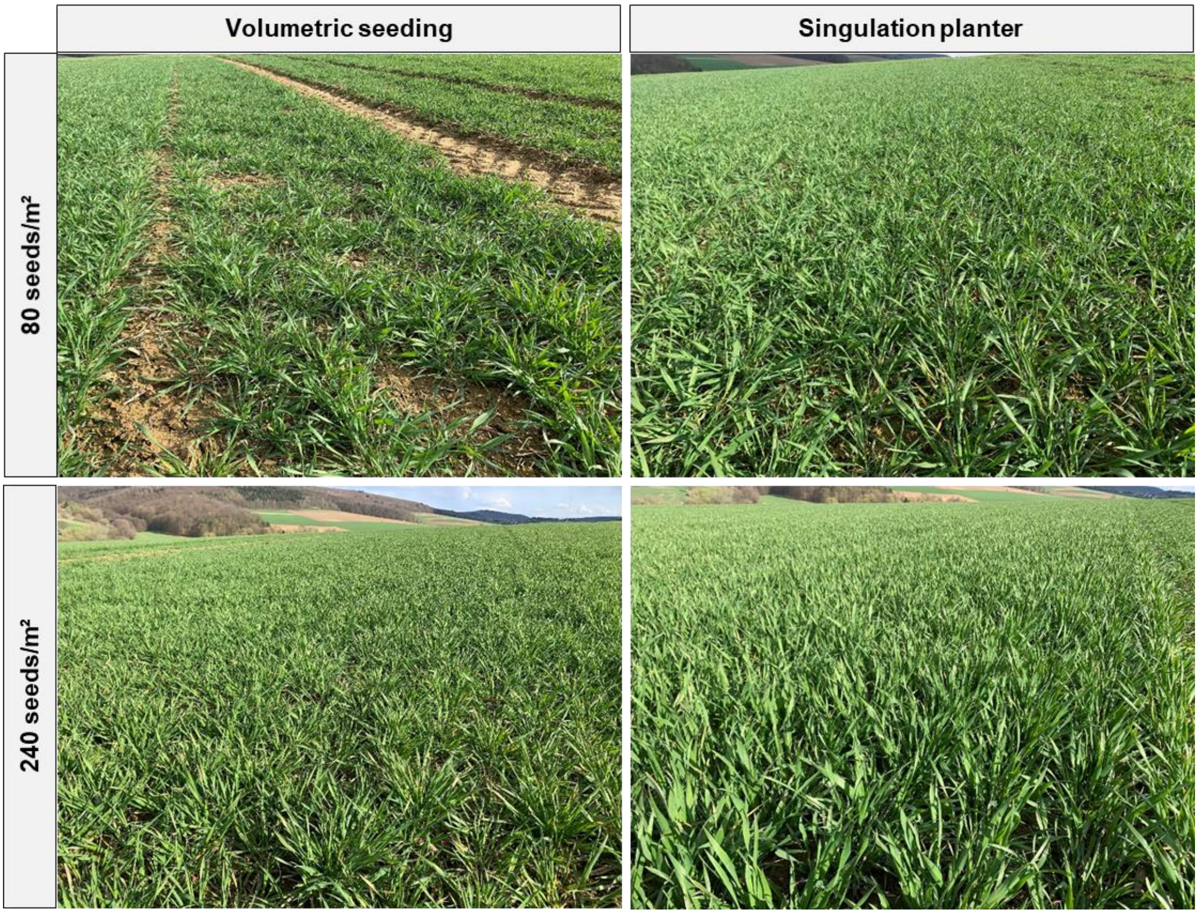

Figure 29: Winter wheat crop growth during stem elongation in spring, comparing soil coverage of volumetric seeding and singulation planter at 80 and 240 seeds/m². Waldems, 2020.

seed densities, higher seed rates are necessary for volumetric seeding to ensure an improved soil coverage.

Taking that into account, a sufficient crop establishment need to be ensured when lower seed rates are used. This dependency has been demonstrated already by weather specific lower emergence rates in HU20 and FR20, that reduced the ability for crop space compensation. To ensure the beneficial yield effects at lower seed densities when using a singulation planter, high seed quality, good seed bed conditions, seed to soil contact, water and temperature are required to ensure a high seed emergence in field.

It can be concluded, that the regression modelling supports in addition hypothesis 2 and 3, that the use of a singulation planter increases winter wheat yield and has also potential to maintain the maximum yield level of the volumetric seed metering at lower seed densities. This is delivering an increased economic return, as higher yields can be achieved at lower seed rates, considering that these differences are higher if seed costs increase, like for hybrid wheat varieties. Although the singulation planter generates higher economic return compared to volumetric seeding in hybrid wheat, regardless costs for seed technique, hybrid wheat has neither potential to outperform non-hybrid wheat in perspective of yield, nor in an economic perspective. However, the potential of the singulation planter is proved in terms of seed cost savings and yield increase, additional cost saving, and sustainability impact can be expected based on savings in plant protection and crop nutrition. Referring to potential future restrictions and limitations likewise the EU Green Deal 2030, it is worthwhile to investigate in further research, as the use of a singulation planter in small grains can be a solution to maintain yield and grain quality at lower input rates.

6. Conclusion

The longitudinal seed distribution in trench can be significantly improved when using a singulation planter. Even though no effects of the improved spacing quality were found in tiller and ear development, significant higher yields were produced. If the plant spacing quality is improved, seed rates can be reduced also while maintaining the maximum agronomic and economic return compared to volumetric seeding. These yield effects are contributed to the reduced intraspecific competition of the wheat plants affecting a more efficient use of water, nutrients and sun light. Hybrid wheat was not able to outperform non-hybrid wheat in the yield perspective, therefore a higher economic return can be achieved with hybrid wheat when improving the plant distribution with the singulation planter. As the higher seed costs of hybrid wheat reduce the economic threshold to lower seed densities, the value of the singulation planter is increased due to the higher yield response at lower seed densities compared to volumetric seeding.

To further increase the value of singulating wheat at lower plant densities and also the value of hybrid wheat, an adaption of crop management practice in terms of applying nitrogen and crop growth regulators need to be considered for future research investigations. Additional research can be added in terms of disease control as improved plant space uniformity and lower seed densities can impact the microclimate and thus the susceptibility against diseases. This could deliver additional cost saving potential or yield increase, while increasing sustainability aspects when growing winter wheat.

7. Summary

As wheat is worldwide one of the most important agricultural grown crops, yield productivity, yield stability and also the single plant efficiency are becoming more important in terms of climate change and potential future restrictions in applying fertilizers and chemical plant protection, like foreseen in the European Green Deal 2030. One option can be hybrid wheat varieties as they are supposed to deliver higher and stable yields especially under resource limited conditions. Also, the plant distribution quality in field has potential for more efficient crop growth with result of higher wheat yields at lower seed densities. Due to the random seed distribution of volumetric seeders, seeds are bunch wise placed, indicated by high ratios of multiple and skipped seeds. As this won't fit the agronomic requirement of individual plant growth spaces, the question was raised if the use of a singulation planter can improve the longitudinal seed spacing quality in winter wheat and how this is affecting yield production. For that reason, research was executed to validate the agronomic potential and also the economic return when singulating winter wheat, considering high and low seed densities and a hybrid vs. non-hybrid winter wheat variety under differing climate conditions in Europe.

Referring to **hypothesis 1**, it was assumed that a singulation planter can significantly improve the longitudinal plant space distribution of winter wheat seeds compared to volumetric seed metering. This was confirmed on the one side by the significant lower coefficient of variation (CoV) of the plant distances in trench and also by a higher amount of seed spacing data hitting the target range of 0.5-1.5 deviation to target mean seed distance and thus indicating the reduction of multiple and skipped seeds in trench. Considering a higher sensitivity of the singulation planter at higher seed rates, a reduced quality of seed space distribution needs to take into account.

The more uniform plant spacing quality when using the singulation planter is an approach to realize the in agronomic perspective required individual plant growth spaces that improves growth efficiency of the individual plants. Based on this assumption it has been analyzed with **hypotheses 2 and 3** if seed singulation of winter wheat can increase grain yield on the one side and also maintains grain yield at lower seed densities compared to volumetric seed metering on the other side. The field data showed that yield production increased due to singulation in average by 0.48 t/ha. Beside that, a more stabilized yield production was delivered at lower seed rates when using the singulation planter. In average, seed rates of 160-200 seeds/m² can maintain the yield production compared to volumetric seeding at higher seed densities which is indicating up to 50 % seed cost savings. But, those potentials highly depend on the climatic and environmental conditions during the growing season. If more resource limitations occur during crop growth, a higher potential of singulating winter wheat can be expected.

With focus on hybrid wheat varieties, it is known that they are supposed to deliver higher and stable grain yields due to a higher resistance against drought and diseases while also having a better nutrient efficiency. Using those insights, it was analyzed with **hypothesis 4**, if hybrid wheat is outperforming non-hybrid wheat in an agronomic perspective. As the average wheat grain yield did not significantly differed between the tested hybrid and non-hybrid wheat varieties, this hypothesis could not be supported. Additional breeding effort and also the adaption in crop management strategies in terms of rate and timing of fertilization are needed to exhaust the yield benefit of hybrid wheat.

As result of the higher seed costs for hybrid wheat seeds, an economic threshold is reached when seed rates exceed densities of 150 seeds/m². At these low densities, the importance of a good seed spacing quality that improves the area use efficiency of the individual plants is increasing. This enhances the importance of the singulation planter, as the yield production is significantly higher at low seed rates compared to volumetric seeding. For that reason, **hypothesis 5** was set to verify if the singulation planter generated a higher economic revenue in hybrid wheat compared to non-hybrid wheat. Based on the regression analysis on yield production, additional revenue can be achieved when seeding hybrid wheat with a singulation planter compared to non-hybrid wheat varieties. This delivers 120 €/ha higher revenue when singulating hybrid wheat as result of a higher yield and higher seed cost savings while the revenue of the non-hybrid wheat delivers 22 €/ha more. This supports **hypothesis 5** as the use of the singulation planter delivers a higher revenue when used for hybrid wheat.

All in all, the use of a singulation planter increases yield in winter wheat while having the potential to reduce seed densities to an agronomic minimum as the area use efficiency and also the intraspecific competition of the individual wheat plants is reduced. This also increases the sustainability aspects of growing winter wheat as the efficiency of wheat plants can be increased while having a lower input rate of seeds needed. As lower, more uniform spaced plant densities are associated with increased nutrient efficiency, less risk for diseases and lodging, additional saving potentials are expected when adjusting rate and timing of nitrogen fertilization and also the application of fungicides and crop growth regulators. With that, seed singulation of winter wheat can help to maintain yield production at lower input rates and so fulfill future limitations in fertilization and crop protection like foreseen in the European Green Deal 2030. Due to those facts it is worthwhile to further investigate in the development of seed singulation concepts that are able to precisely singulate and place cereal seeds in trench while maintaining productivity and ease of use during handling and executing the seeding operation.

8. Zusammenfassung

Weizen ist eine der weltweit wichtigsten landwirtschaftlichen Nutzpflanzen. Daher werden Ertragsproduktivität, Ertragsstabilität und auch die Einzelpflanzeneffizienz im Hinblick auf den Klimawandel und potentiell zukünftige Einschränkungen bei der Anwendung von Düngemitteln und chemischem Pflanzenschutz, wie im „European Green Deal 2030“ vorgesehen, immer wichtiger. In diesem Kontext könnten zukünftig auch Hybridweizensorten eine größere Rolle spielen, da ihnen die Eigenschaft zugesprochen wird, unter Ressourcen limitierenden Bedingungen höhere und stabilere Erträge zu realisieren. Auch die Optimierung der Pflanzenverteilung im Feld hat Potential für ein effizienteres Pflanzenwachstum, welches zu höheren Erträgen bei geringeren Saatraten führen kann. Aufgrund der zufälligen Saatgutverteilung von volumetrisch-dosierenden Sämaschinen wird das Saatgut in der Reihe oftmals sehr ungleichmäßig platziert, wodurch hohe Anteile von Lücken zwischen den Pflanzen bei gleichzeitig zu eng stehenden Pflanzen entstehen. Diese Bedingungen führen zu einer ungleichmäßigen Entwicklung der Einzelpflanzen und zu Nachteilen in der Ertragsbildung. Daher wurde die Frage gestellt, ob mit dem Einsatz einer Einzelkornsämaschine die Längsabstände in der Reihe von Winterweizen verbessert werden können und ob dies die Ertragsbildung beeinflusst. Aus diesem Grund wurde mit dieser Studie das agronomische Potential als auch der wirtschaftliche Ertrag bei der Vereinzelung von Winterweizen unter Berücksichtigung von hohen und niedrigen Saatraten in Kombination mit zwei Sorten (Linien- vs. Hybrid-Sorte) an unterschiedlichen Standorten in Europa untersucht.

Bezugnehmend zu Hypothese 1 wurde angenommen, dass eine Einzelkornsämaschine die Längsverteilung der Winterweizenpflanzen im Vergleich zur volumetrischen Saatgutdosierung signifikant verbessern kann. Dies wurde zum einen durch den signifikant geringeren Variationskoeffizienten (CoV) der Pflanzabstände in der Reihe und durch höhere Anteile von Pflanzenabständen im Zielbereich der 0.5-1.5 fachen Abweichung zum mittleren Saatgutabstand belegt. Damit konnten in der Reihe die Anteile der Lücken als auch der zu eng stehenden Pflanzen reduziert werden. Da die Einzelkornsämaschine bei Zunahme der Saatraten empfindlicher reagiert, muss mit einer verringerten Qualität in der Standraumverteilung bei höheren Raten gerechnet werden.

Die durch Saatgutvereinzelung verbesserte Standraumverteilung ist ein Ansatz, um die aus agronomischer Sicht erforderlichen individuellen Pflanzenstandräume zu generieren, wodurch die Effizienz der Einzelpflanze gesteigert werden kann. Basierend auf dieser Annahme wurde mit den Hypothesen 2 und 3 untersucht, ob die Vereinzelung von Winterweizen einerseits den Kornertrag steigert und andererseits den Kornertrag bei geringeren Saatraten im Vergleich zur volumetrischen Saatgutdosierung erhält. In den Feldversuchen wurde belegt, dass die Vereinzelung den Kornertrag im Mittel um 0.48 t/ha steigert. Weiterhin wurden bei Anwendung der Saatgutvereinzelung stabilere Erträge bei geringeren Saatraten erzielt. Im Mittel können Saatraten von 160-200 Körner/m² die Kornertragsproduktion im Vergleich zur volumetrischen

Saatgutdosierung bei höheren Saatraten aufrechterhalten, was Einsparungen des Saatgutes von bis zu 50 % entspricht. Das Potenzial der Vereinzelung hängt jedoch stark von den Klima- und Umweltbedingungen während der Vegetationsperiode ab. Ist während der Vegetation mit höheren Einschränkungen in der Ressourcenverfügbarkeit zu rechnen, kann mit einem höheren Ertragseffekt durch Saatgutvereinzelung gerechnet werden.

Beim Hybridweizen ist bekannt, dass dieser aufgrund einer höheren Resistenz gegenüber Trockenheit und Krankheiten bei gleichzeitig besserer Nährstoffeffizienz einen höheren und stabileren Kornertrag bildet. Davon ausgehend wurde mit Hypothese 4 untersucht, ob Hybridweizen in der Ertragsleistung gegenüber Linienweizen überlegen ist. Da sich der mittlere Kornertrag der getesteten Hybrid- und Linienweizensorten nicht signifikant unterschied, konnte diese Hypothese nicht gestützt werden. Um den Ertragsvorteil von Hybridweizen besser ausschöpfen zu können, wären zusätzlicher züchterischer Aufwand als auch die Anpassung der Anbaustrategien im Feld in Bezug auf Rate und Zeitpunkt der Düngung erforderlich.

Aufgrund der hohen Saatgutkosten für Hybridweizen wird die ökonomische Schwelle bereits bei Saatraten über 150 Körner/m² erreicht. Die geringeren Saatraten erfordern jedoch eine gute Längsverteilung der Pflanzen in der Reihe, um eine möglichst hohe Nutzungseffizienz der Einzelpflanze zu generieren. Damit erhöht sich der Effekt der Saatgutvereinzelung, da die Ertragseffekte bei geringeren Saatraten höher im Vergleich zur volumetrischen Saatgutdosierung sind. Aufgrund dessen wurde mit Hypothese 5 untersucht, ob die Vereinzelung von Hybridweizen im Vergleich zu Linienweizen einen höheren wirtschaftlichen Ertrag erzeugt. Basierend auf der Regressionsanalyse zur Ertragsproduktion erzielt die Vereinzelung von Hybridweizen deutliche Mehrerlöse im Vergleich zur Vereinzelung von Linienweizen. Im Hybridweizen wurden mit der Vereinzelung 120 €/ha Erlös durch höheren Ertragszuwachs bei zusätzlichen Einsparungen von teurerem Saatgut realisiert, während dieser bei 22 €/ha zusätzlichem Erlös im Linienweizen lag. Hypothese 5 wird damit gestützt, da die Vereinzelung von Hybridweizen einen höheren Erlös gegenüber Linienweizen bringt.

Als Resultat der verbesserten Flächennutzungseffizienz der Einzelpflanze bei gleichzeitig reduzierter intraspezifischen Konkurrenz zwischen den Pflanzen, kann mit dem Einsatz einer Saatgutvereinzelung im Weizen der Kornertrag gesteigert werden, mit dem Potenzial, die Saatraten auf ein agronomisches Minimum zu reduzieren. Damit erhöht sich die Nachhaltigkeit des Weizenanbaus, da die Effizienz der Weizenpflanzen gesteigert wird, bei gleichzeitig verringertem Bedarf an Saatgut. Zudem sind geringere Pflanzendichten bei gleichmäßigerer Verteilung mit einer höheren Nährstoffeffizienz sowie einem geringerem Krankheits- und Lagerrisiko verbunden, weshalb zusätzliche Einsparpotenziale durch Anpassung von Zeitpunkt und Rate der Stickstoffdüngung sowie der Anwendung von Fungiziden und Wachstumsregulatoren erwartet werden.

Auf diese Weise bietet die Saatgutvereinzelung eine Möglichkeit, die Ertragsproduktion von Weizen bei verringertem Mitteleinsatz aufrechtzuerhalten, wodurch zukünftige Einschränkungen bei Düngung und Pflanzenschutz, wie im „European Green Deal 2030“ vorgesehen, unterstützt werden können. Aufgrund dieser Ergebnisse ist es lohnenswert, weiter in die Entwicklung einer Technik zur präzisen Saatgutvereinzelung für Getreide zu investieren, sodass Produktivität, Bedienungsfreundlichkeit sowie die Handhabung während Ausführung der Aussaat nicht negativ beeinflusst werden.

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Appendix

Table A 1: Variety specific characteristics of the in field trial tested winter wheat. (Derived from BUNDESSORTENAMT (2021) [13])

Characteristics of tested winter wheat varieites			
		SU Hymalaya	**RGT Reform**
General characteristics	Ear emergence	5	5
	Maturity	6	5
	Plant length	6	3
	Winter damage	-	4
	Lodging	5	4
Yield parameters	Tiller potential	5	6
	Grains / Ear	7	5
	TKW	5	6
	Yield performance	8	7
Grain quality parameters	Falling number	6	9
	Stability of falling number	+	+
	Protein	2	4
	Quality	A	A

Table A 2: ANOVA summary for winter wheat seed emergence, reflecting technique (Tec), seed rate (SR), variety (V) and Test Site (TS) and its interactions.

Emergence rate: Type I Analysis of Variance Table with Kenward-Roger's method							
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	
Tec	0.227	0.227	1	5.54	17.390	0.007	**
SR	3.134	1.045	3	244.29	79.872	< 0.001	***
V	0.467	0.467	1	2.77	35.672	0.012	*
Tec x SR	0.135	0.045	3	244.29	3.438	0.018	*
Tec x V	0.000	0.000	1	5.54	0.011	0.919	
SR x V	0.006	0.002	3	244.29	0.155	0.926	
Tec x SR x V	0.076	0.025	3	244.29	1.938	0.124	
TS	4.344	0.869	5	245.57	66.433	< 0.001	***
Tec x TS	2.379	0.476	5	246.7	36.377	< 0.001	***
SR x TS	0.990	0.066	15	244.29	5.048	< 0.001	***
V x TS	0.457	0.091	5	242.72	6.980	< 0.001	***
Tec x SR x TS	0.814	0.054	15	244.29	4.148	< 0.001	***
Tec x V x TS	0.217	0.043	5	246.7	3.311	0.007	**
SR x V x TS	0.213	0.014	15	244.29	1.085	0.370	
Tec x SR x V x TS	0.326	0.022	15	244.29	1.662	0.059	.

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 3: ANOVA summary for coefficient of variation of winter wheat plant distances, reflecting technique (Tec), seed rate (SR), variety (V) and Test Site (TS) and its interactions.

Coeficient of variation: Type I Analysis of Variance Table with Kenward-Roger's method						
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Tec	6.378	6.378	1	5.54	242.305	< 0.001 ***
SR	0.690	0.230	3	244.36	8.743	< 0.001 ***
V	0.002	0.002	1	2.77	0.092	0.783
Tec x SR	0.675	0.225	3	244.36	8.544	< 0.001 ***
Tec x V	0.022	0.022	1	5.54	0.850	0.395
SR x V	0.036	0.012	3	244.36	0.452	0.716
Tec x SR x V	0.075	0.025	3	244.36	0.945	0.419
TS	1.683	0.337	5	242.79	12.783	< 0.001 ***
Tec x TS	0.487	0.097	5	246.78	3.697	0.003 **
SR x TS	1.116	0.074	15	244.36	2.827	< 0.001 ***
V x TS	0.151	0.030	5	242.79	1.147	0.336
Tec x SR x TS	0.204	0.014	15	244.36	0.517	0.930
Tec x V x TS	0.075	0.015	5	246.78	0.569	0.724
SR x V x TS	0.220	0.015	15	244.36	0.558	0.904
Tec x SR x V x TS	0.328	0.022	15	244.36	0.831	0.642

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 4: ANOVA summary for plant losses over winter of winter wheat plants, reflecting technique (Tec), seed rate (SR), variety (V), Test Site (TS) and its interactions.

Plant losses over winter: Type I Analysis of Variance Table with Kenward-Roger's method						
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Tec	1387	1387	1	5.54	2.356	0.180
SR	25104	8367.9	3	116.3	14.216	< 0.001 ***
V	224	224.4	1	2.77	0.381	0.584
Tec x SR	656	218.7	3	116.3	0.372	0.774
Tec x V	551	551	1	5.54	0.936	0.374
SR x V	1355	451.6	3	116.3	0.767	0.515
Tec x SR x V	2680	893.4	3	116.3	1.518	0.214
TS	36417	18208.5	2	118.09	30.929	< 0.001 ***
Tec x TS	499	249.7	2	120.08	0.424	0.655
SR x TS	6634	1105.7	6	116.3	1.878	0.090 .
V x TS	92	45.9	2	116.12	0.078	0.925
Tec x SR x TS	1589	264.9	6	116.3	0.450	0.844
Tec x V x TS	147	73.5	2	120.08	0.125	0.883
SR x V x TS	756	126	6	116.3	0.214	0.972
Tec x SR x V x TS	614	102.4	6	116.3	0.174	0.983

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 5: ANOVA summary for winter wheat tiller density, reflecting technique (Tec), seed rate (SR), variety (V), Test Site (TS) and its interactions.

Tiller density: Type I Analysis of Variance Table with Kenward-Roger's method						
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Tec	429	429	1	6	0.023	0.886
SR	1490960	496987	3	132	26.039	< 0.001 ***
V	2759	2759	1	3	0.145	0.729
Tec x SR	19117	6372	3	132	0.334	0.801
Tec x V	1215	1215	1	6	0.064	0.809
SR x V	89769	29923	3	132	1.568	0.200
Tec x SR x V	62077	20692	3	132	1.084	0.358
TS	2592543	1296271	2	132	67.917	< 0.001 ***
Tec x TS	84565	42282	2	132	2.215	0.113
SR x TS	156565	26094	6	132	1.367	0.232
V x TS	8276	4138	2	132	0.217	0.805
Tec x SR x TS	241450	40242	6	132	2.108	0.056 .
Tec x V x TS	27427	13713	2	132	0.719	0.489
SR x V x TS	124746	20791	6	132	1.089	0.372
Tec x SR x V x TS	85956	14326	6	132	0.751	0.610

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 6: ANOVA summary for numbers of tillers per plant of winter wheat, reflecting technique (Tec), seed rate (SR), variety (V), Test Site (TS) and its interactions.

Tillers per plant: Type I Analysis of Variance Table with Kenward-Roger's method						
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Tec	30.41	30.406	1	6	24.246	0.003 **
SR	310.56	103.52	3	132	82.547	< 0.001 ***
V	0.04	0.042	1	3	0.033	0.867
Tec x SR	2.96	0.987	3	132	0.787	0.503
Tec x V	0.14	0.137	1	6	0.109	0.753
SR x V	5.19	1.728	3	132	1.378	0.252
Tec x SR x V	0.95	0.317	3	132	0.253	0.859
TS	417.11	208.555	2	132	166.302	< 0.001 ***
Tec x TS	0.39	0.193	2	132	0.154	0.857
SR x TS	31.29	5.215	6	132	4.158	< 0.001 ***
V x TS	3.56	1.779	2	132	1.418	0.246
Tec x SR x TS	7.84	1.307	6	132	1.042	0.401
Tec x V x TS	0.07	0.036	2	132	0.029	0.972
SR x V x TS	7.42	1.237	6	132	0.986	0.437
Tec x SR x V x TS	9.19	1.532	6	132	1.222	0.299

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 7: ANOVA summary for winter wheat tiller reduction, reflecting technique (Tec), seed rate (SR), variety (V), Test Site (TS) and its interactions.

Tiller reduction: Type I Analysis of Variance Table with Kenward-Roger's method							
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	
Tec	658	658	1	6	0.052	0.827	
SR	671259	223753	3	132	17.793	< 0.001	***
V	59996	59996	1	3	4.771	0.117	
Tec x SR	15373	5124	3	132	0.408	0.748	
Tec x V	1	1	1	6	0.000	0.992	
SR x V	37201	12400	3	132	0.986	0.401	
Tec x SR x V	30824	10275	3	132	0.817	0.487	
TS	235919	117960	2	132	9.381	< 0.001	***
Tec x TS	72522	36261	2	132	2.884	0.059	.
SR x TS	83861	13977	6	132	1.112	0.359	
V x TS	23558	11779	2	132	0.937	0.395	
Tec x SR x TS	141013	23502	6	132	1.869	0.091	.
Tec x V x TS	17548	8774	2	132	0.698	0.500	
SR x V x TS	75384	12564	6	132	0.999	0.429	
Tec x SR x V x TS	64716	10786	6	132	0.858	0.528	

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 8: ANOVA summary for winter wheat ear density, reflecting technique (Tec), seed rate (SR), variety (V), Test Site (TS) and its interactions.

Ear density: Type I Analysis of Variance Table with Kenward-Roger's method							
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)	
Tec	32031	32031	1	5.54	8.337	0.030	*
SR	720916	240305	3	244.35	62.547	< 0.001	***
V	120438	120438	1	2.77	31.348	0.014	*
Tec x SR	2940	980	3	244.35	0.255	0.858	
Tec x V	153	153	1	5.54	0.040	0.849	
SR x V	6001	2000	3	244.35	0.521	0.668	
Tec x SR x V	3892	1297	3	244.35	0.338	0.798	
TS	3943539	788708	5	243.34	205.224	< 0.001	***
Tec x TS	246508	49302	5	246.76	12.830	< 0.001	***
SR x TS	173713	11581	15	244.35	3.014	< 0.001	***
V x TS	16012	3202	5	242.78	0.833	0.527	
Tec x SR x TS	58488	3899	15	244.35	1.015	0.440	
Tec x V x TS	39066	7813	5	246.76	2.033	0.075	.
SR x V x TS	94301	6287	15	244.35	1.636	0.065	.
Tec x SR x V x TS	81217	5414	15	244.35	1.409	0.143	

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 9: ANOVA summary for numbers of ears per plant of winter wheat, reflecting technique (Tec), seed rate (SR), variety (V), Test Site (TS) and its interactions.

Ears per plant: Type I Analysis of Variance Table with Kenward-Roger's method						
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Tec	3.29	3.291	1	5.592	8.221	0.031 *
SR	339.06	113.021	3	244.292	282.289	< 0.001 ***
V	0.69	0.686	1	2.796	1.714	0.288
Tec x SR	0.54	0.179	3	244.292	0.448	0.719
Tec x V	0.03	0.026	1	5.592	0.066	0.807
SR x V	1.29	0.429	3	244.292	1.072	0.362
Tec x SR x V	0.53	0.178	3	244.292	0.445	0.721
TS	259.33	51.866	5	243.358	129.506	< 0.001 ***
Tec x TS	9.11	1.822	5	246.822	4.549	< 0.001 ***
SR x TS	68.05	4.537	15	244.292	11.332	< 0.001 ***
V x TS	10.08	2.016	5	243.358	5.034	< 0.001 ***
Tec x SR x TS	15.03	1.002	15	244.292	2.502	0.002 **
Tec x V x TS	4.5	0.899	5	246.822	2.245	0.050 .
SR x V x TS	7.14	0.476	15	244.292	1.189	0.280
Tec x SR x V x TS	13.84	0.923	15	244.292	2.305	0.004 **

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 10: ANOVA summary for winter wheat grain yield, reflecting technique (Tec), seed rate (SR), variety (V), Test Site (TS) and its interactions.

Grain yield: Type I Analysis of Variance Table with Kenward-Roger's method						
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Tec	12.77	12.77	1	5.604	31.062	0.002 **
SR	64.22	21.407	3	242.24	52.069	< 0.001 ***
V	0.1	0.101	1	2.883	0.245	0.656
Tec x SR	7.75	2.584	3	242.219	6.285	< 0.001 ***
Tec x V	0.6	0.604	1	5.605	1.469	0.274
SR x V	2.54	0.847	3	242.201	2.059	0.106
Tec x SR x V	0.29	0.098	3	242.211	0.239	0.869
TS	1159.02	231.804	5	243.294	563.824	< 0.001 ***
Tec x TS	16.24	3.249	5	244.768	7.901	< 0.001 ***
SR x TS	52.12	3.474	15	242.226	8.451	< 0.001 ***
V x TS	8.49	1.698	5	243.217	4.131	0.001 **
Tec x SR x TS	10.26	0.684	15	242.243	1.663	0.059 .
Tec x V x TS	5.8	1.16	5	244.811	2.822	0.017 *
SR x V x TS	6.52	0.435	15	242.247	1.057	0.398
Tec x SR x V x TS	4.91	0.327	15	242.263	0.796	0.682

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 11: ANOVA summary for winter wheat grain weight, reflecting technique (Tec), seed rate (SR), variety (V), Test Site (TS) and its interactions.

Grain weight: Type I Analysis of Variance Table with Kenward-Roger's method						
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Tec	23.2	23.2	1	5.516	6.981	0.042 *
SR	2.9	0.98	3	242.412	0.295	0.829
V	212.9	212.88	1	2.759	64.062	0.005 **
Tec x SR	2.4	0.79	3	242.403	0.238	0.870
Tec x V	3.9	3.85	1	5.518	1.160	0.326
SR x V	13.3	4.44	3	242.388	1.336	0.263
Tec x SR x V	33.1	11.04	3	242.404	3.321	0.020 *
TS	14391.6	2878.31	5	242.771	866.015	< 0.001 ***
Tec x TS	63.6	12.71	5	244.798	3.824	0.002 **
SR x TS	271.7	18.12	15	242.427	5.452	< 0.001 ***
V x TS	98.7	19.75	5	240.929	5.940	< 0.001 ***
Tec x SR x TS	58.7	3.91	15	242.454	1.177	0.290
Tec x V x TS	20.1	4.02	5	244.864	1.210	0.305
SR x V x TS	64.8	4.32	15	242.464	1.299	0.203
Tec x SR x V x TS	53.8	3.59	15	242.492	1.079	0.377

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 12: ANOVA summary for numbers of grains per ear of winter wheat, reflecting technique (Tec), seed rate (SR), variety (V), Test Site (TS) and its interactions.

Grains per ear: Type I Analysis of Variance Table with Kenward-Roger's method						
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Tec	61.5	61.5	1	5.516	1.034	0.352
SR	2879.9	960	3	242.383	16.134	< 0.001 ***
V	2995.1	2995.1	1	2.758	50.339	0.008 **
Tec x SR	100.9	33.6	3	242.375	0.565	0.638
Tec x V	10.7	10.7	1	5.517	0.180	0.687
SR x V	81	27	3	242.355	0.454	0.715
Tec x SR x V	297	99	3	242.37	1.664	0.175
TS	23272	4654.4	5	243.622	78.220	< 0.001 ***
Tec x TS	2832.8	566.6	5	244.757	9.521	< 0.001 ***
SR x TS	1391.7	92.8	15	242.396	1.559	0.086 .
V x TS	456.3	91.3	5	240.904	1.533	0.180
Tec x SR x TS	1091.6	72.8	15	242.422	1.223	0.255
Tec x V x TS	479.6	95.9	5	244.84	1.612	0.158
SR x V x TS	1326.4	88.4	15	242.425	1.486	0.111
Tec x SR x V x TS	1149	76.6	15	242.449	1.287	0.210

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 13: ANOVA summary for winter wheat grain protein content, reflecting technique (Tec), seed rate (SR), variety (V), Test Site (TS) and its interactions.

Grain protein content: Type I Analysis of Variance Table with Kenward-Roger's method						
	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Tec	2.11	2.112	1	5.516	11.698	0.016 *
SR	20.84	6.945	3	242.368	38.463	< 0.001 ***
V	11.66	11.663	1	2.758	64.588	0.005 **
Tec x SR	1.12	0.374	3	242.359	2.072	0.105
Tec x V	0.04	0.037	1	5.517	0.202	0.670
SR x V	0.28	0.092	3	242.337	0.511	0.675
Tec x SR x V	0.15	0.05	3	242.35	0.280	0.840
TS	1059.26	211.853	5	243.4	1173.198	< 0.001 ***
Tec x TS	1.28	0.257	5	244.732	1.423	0.217
SR x TS	8.69	0.579	15	242.38	3.209	< 0.001 ***
V x TS	4.54	0.909	5	240.892	5.030	< 0.001 ***
Tec x SR x TS	3.6	0.24	15	242.405	1.328	0.186
Tec x V x TS	0.5	0.101	5	244.828	0.558	0.732
SR x V x TS	1.35	0.09	15	242.401	0.497	0.941
Tec x SR x V x TS	2.17	0.144	15	242.423	0.800	0.677

*Signif. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; '.' p<0.1*

Table A 14: Regression parameter of winter wheat grain protein content and its dependency on grain yield merged for all factors

Regression analysis: *Protein ~ Yield*			
Predictors	*Estimates*	*CI*	*p*
(Intercept)	17.94	17.33 – 18.56	**<0.001**
Yield	-0.65	-0.71 – -0.59	**<0.001**
Observations	350		
R^2 / R^2 adjusted	0.533 / 0.532		

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Formal declaration

Erklärung gemäß der Promotionsordnung des Fachbereich 09 vom 07. Juli 2004 § 17 (2)

Ich erkläre: Ich habe die vorgelegte Dissertation selbständig und ohne unerlaubte fremde Hilfe und nur mit den Hilfen angefertigt, die ich in der Dissertation angegeben habe. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Bei den von mir durchgeführten und in der Dissertation erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in der „Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis" niedergelegt sind, eingehalten.

I declare: this dissertation submitted is a work of my own, written without any illegitimate help by any third party and only with materials indicated in the dissertation. I have indicated in the text where I have used texts from already published sources, either word for word or in substance, and where I have made statements based on oral information given to me. At any time during the investigations carried out by me and described in the dissertation, I followed the principles of good scientific practice as defined in the "Statutes of the Justus Liebig University Giessen for the Safeguarding of Good Scientific Practice".

Giessen, 11. December 2021

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