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Doctoral Thesis

Yield response of hybrid and line wheat cultivars to varying site and growing conditions and delayed sowing time

submitted by

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Giessen, 06/22/2023

DOI: http://dx.doi.org/10.22029/jlupub-18384

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List of abbreviations

°	Degree
ANOVA	Analysis of variance
app.	Application
C	Centigrade
CHAs	Chemical hybridizing agents
cm	Centimeter
CI	Confidence interval
cld	Compact letter display
CO_2	Carbon dioxide
CT	Cultivar type (Hybrid/Line)
CV	Cultivar
diff.	Difference
DF	Degrees of freedom in the source.
dt	Decitonne
EI	Environmental Index
g	Gram
GDD	Growth degree-days
GEI	Genotype-Environment-Index
GG	Gross Gerau
Gi	Giessen
GR	Global radiation
GYD	Grain yield differences
GYH	Grain yield Hybrids
GYL	Grain yield Lines
GYDH	Grain yield differences Hybrids
GYDL	Grain yield differences Lines
H	Hybrids
ha	Hectare
K_2O	Potassium oxide
K_{CAL}	Potassium (Calcium-acetate-lactate)
kg	Kilogramm
km	Kilometer

L	Lines
m	Meter
m^2	Square meter
Mg	Magnesium
mg	Milligram
MS	Mean of sum of squares due to the source
N	Nitrogen
N_{min}	Mineral nitrogen
NO_3^-	Nitrate
TNOD	Total number of days
P	Phosphor
PPT	Precipitation
PAR	Photosynthetically active radiation
P_{CAL}	Phosphorous (Calcium-acetate-lactate)
RH	Rauischholzhausen
SDM	Standard deviation of the mean
SE	Standard error
SS	Sum of squares due to the source
ST	Sowing time
S1	Early sowing time
S2	Late sowing time
t	Tonne
T_b	Base temperature
T_{min}	Minimum temperature
T_{max}	Maximum temperature
yr	Year

1 Introduction

Increasing crop production and producing high-quality food is necessary due to the rapidly growing human population. Climate change, heat stress, water scarcity and devastation of agricultural land due to industrialization are threatening the food production chain and alarming the issue of supplying food for an ever-growing population in the future. Cereals, especially wheat, are the main food of human beings in the whole world. Wheat has a major role as a staple food, where the production of grains with high quality converges with the importance of food production in world increasing population. Despite the fact that wheat output expanded greatly in the twentieth century (Ray et al., 2013) due to genetic improvement of wheat varieties (Grassini et al., 2013), the need for additional wheat remains.

According to FAO estimates, the world will require approximately 840 million t of wheat by 2050, a significant increase from the present production level of 642 million t (Sharma et al., 2015). As a result, the food supply will need to increase by 2-3% per year to fulfil the expected demand. However, yields of the key grains, like rice, maize, and wheat, have increased at less than half of this rate in the recent decade (Ray et al., 2013). Many studies and efforts have been done to increase the potential yield of wheat crops and novel methods deployed to increase yield stability of wheat crops in model approaches (Bocci et al., 2020; Weedon et al., 2019; Cheshkova et al., 2020; Liu et al., 2017; Mühleisen et al., 2014) or sustainable cropping systems (Macholdt et al., 2020; Chen et al., 2018). Among them the United States, Canada, Australia, China, India, and a few European countries, notably France, Germany and Russia, are counted as the world's largest wheat producers (Helman et al., 2022).

According to the results of the special harvest and quality study in Germany, the production of winter wheat, the most common type of grain farmed in Germany, in 2022 was about 21.1 million t. In comparison to 2020, this was a drop of 657,200 t, or 3%. According to the results of the land use study, winter wheat was planted on 2.9 million hectares in 2021 (Statistisches Bundesamt, 2022).

Crop breeding is definated as “the art and science of improving the heredity of plants for the benefit of humankind” (Sleper and Poehlman, 2006). Plant breeders should focus their efforts on traits with the most significant potential for increasing production. The traits that have been improved by crop breeding include: yield increasing the grain production on the same amount of land (Calderini et al., 1995; Sanchez-Garcia et al., 2013; Tshikunde et al., 2019), resistance to pests and diseases (Mondal et al., 2016; Summers et al., 2013; Bisht et al., 2019; Bigini et al., 2021), adaptation to environmental stresses such as heat, drought, frost (Trethowan et al., 2008; Langridge et al., 2021; Dhankher et al., 2018) and lodging (Foulkes et al., 2011; Shah et al., 2019; Khobra et al., 2019), nutritional value (Amiri et al., 2018; Chandra et al., 2020; Uauy et al., 2006), ease of harvest (Boden et al., 2015). Therefore, new technologies must be developed to speed up breeding by enhancing genotyping and phenotyping methodologies and increasing the genetic diversity of breeding germplasm accessibility (Tester and Langridge, 2010).

So far, numerous parameters in current wheat varieties have developed. Each of these traits can be essential in terms of quantity, physiology, nutrition or resistance to biotic and abiotic stresses. Some of the crucial parameters in wheat grain and biomass production include plant height, numbers of tillers, thousand kernel weight, root growth, stomatal conductance and photosynthetic rate, water and nutrient consumption efficiency, disease, and stress resistance (Calderini et al., 1995; Reynolds et al., 2009). Several studies have found that new modern varieties can outperform older varieties in poor and optimal agronomic conditions (Ortiz-Monasterio et al., 1997; Calderini and Slafe, 1999; De Vita et al., 2010).

Wheat and barley with high yield potential are more likely to produce higher yields under favorable environmental conditions than under stress conditions. In addition, wheat and barley with higher resistance to environmental stress such as drought (Reinhardt et al., 2021), diseases, heat or frost (Sutka and Galiba, 2003), lack of nutrients and soil compactions will also show increased grain yield in high-yield environments. However, it is becoming increasingly apparent that specific selection strategies are needed to enhance the yield of wheat crops in low yield environments (Richards, 1992).

Climate change affects agricultural production systems and cultivated crops worldwide (Jägermeyr et al., 2021; Shew et al., 2020; Ceccarelli et al., 2007). Extreme weather events have had a negative effect on cereal crop output due to climate change, and Europe has been affected more frequently by rainfall deficiencies, resulting in yield losses (Jägermeyr et al., 2021; Beillouin et al., 2020; Ciais et al., 2005). Dry spring periods in particular have a negative impact on plant development and the yield performance of cereal crops. This effect is comparatively more pronounced for later developing wheat than for barley or rye. Moreover, this relationship is even closer on sandy soils than on clay and loamy soils with higher water capacity (Reinhardt et al., 2021). To mitigate these negative effects more efforts are being made to enhance or stabilize crop output and quality in the face of dynamic environmental and biotic risks such as drought stress, which will be triggered by rapid global environmental change. Increased yield in abiotic challenges like drought could best be achieved by selecting cereal or wheat varieties with higher yields under optimal production conditions (Sah et al., 2016).

In a three-year analysis of ninety winter wheat varieties in Germany between 1966 and 2007, Ahlemeyer and Friedt (2011) found that continued genetic innovations might increase grain output by 0.034 to 0.038 t ha^{-1} yr^{-1}. It also suggested that environmental conditions significantly affect grain yield performance, and that breeding is critical in adapting varieties to these conditions. In this regard, the superiority of modern variety is estimated at 0.66% yr^{-1} in low management intensity compared to 1.16% yr^{-1} in high management intensity practices (Laidig et al., 2014).

Heterosis is widely used to increase yield in inbreeding crops while also lowering costs by improving production efficiency. The success of hybrid breeding depends on the percentage of heterosis and the availability of a cost-effective hybrid-seed-production-system. Hybrid breeding is successful in many crops like maize because of the high magnitude of heterosis (Duvick, 1997). Hybrid rice exhibits 15 to 20% heterosis compared to line rice (Xiao et al., 1995; Virmani and Kumar, 2004). In rye the hybrids show higher grain yield (from 4.65 t/ha to 6.07 t/ha) in comparison with the lines (Ismagilov et al., 2022; Haffke et al., 2015) and sugar beet (Curcic et al., 2018)

In self-pollinated cereals such as wheat and triticale, hybrids outperform lines by about 10% heterosis (Martin et al., 1995; Oury et al., 2000; Oettler et al., 2005; Fischer et al., 2010). In various studies across environments and countries, the yield performance of hybrid wheat varieties was compared to that of parental inbred lines or other adapted inbred lines (e.g., Bruns and Peterson, 1998; Corbellini et al., 2002; Koemel et al., 2004; Gowda et al., 2010; Longin et al., 2013). In convergence in Italy, Corbellini et al. (2002) found different traits of heterosis among wheat varieties, which varied from 3.5% in one data set to 15% in another. In North America, the average yield advantage of hybrid wheats compared to lines was stated about 10% (Bruns and Peterson, 1998; Koemel et al., 2004). In addition, in France, Oury et al. (2000) showed the average heterosis of wheat varieties of about 10%, which is in line with the wheat average heterosis levels of 10.7% in Germany shown by Longin et al. (2013).

Changes in the environment, such as drought stress or high precipitation events, threaten yield stability and increase market volatility. As a result, yield stability is an important feature of production besides increasing yield potential (Macholdt and Honermeier, 2017). Several studies compared different stability parameters in experimental datasets (e.g., Becker, 1981, Piepho and Lotito, 1992). It found that a genotype might be stable according to one stability parameter but unstable according to another one. Increased yield stability is frequently attributed to hybrids compared to lines (Longin et al., 2012). Crow (1998) stated the higher drought resistance of hybrids, which can be interpreted as higher yield stability. Thus, hybrids can better buffer variable environmental conditions, including abiotic stress, compared to lines. Multiple traits, such as resistance to diseases, nitrogen use efficiency, the ability for tillering, frost and drought tolerance, can contribute to the complex trait “yield stability,” and their relevance and contribution depend on the specific environments (Piepho, 1998).

Objectives of the study

Most research investigations focus solely on wheat grain yields, neglecting to consider yield stability. In addition, data on hybrid vs. line yield performance of wheat in high- and low-yield environments are rare. Furthermore, there is limited knowledge on the yield performance of wheat hybrids vs. lines at various sowing times. Therefore, the following were the main objectives of this study carried out with winter wheat:

(1) To characterize the effects of varying site and growing conditions on grain yields of wheat hybrids compared to line cultivars.

(2) To clarify the effect of delayed sowing time on grain yield reaction of wheat hybrids compared to line cultivars.

(3) To clarify whether there are differences between hybrid and line cultivars in terms of yield stability.

(4) To verify that varying environmental conditions have less effect on performance of hybrid wheat than line cultivars.

(5) To verify that wheat hybrids are characterized by higher yield stability compared to line cultivars.

2 Literature review

2.1 Taxonomic classification of wheat

Wheat is a member of the *Poaceae* family and belongs to the genus *Triticum*. According to chromosome number sets, the genus *Triticum* is classified into three groups (Campbell, 2023; Sakamura, 1918). The ancient, cultivated group are diploids with 14 (n=7) chromosomes like *Triticum boeoticum*, *Triticum urartu*, *Triticum monococcum* (2n = 2x = 14, AA), which are known as einkorn group of wheats (Kilian et al., 2007). Tetraploid wheats have 28 (n=14) like *T. dicoccoides*, *T. durum* and *Triticum araraticum* (2n = 4x = 28, AABB) which are classified as emmer wheat (Adonina et al., 2015; Golovnina et al., 2007). The hexaploid wheats have 42 (n=21) chromosomes like *Triticum aestivum* and *T. compactum* (2n = 6x = 42, AABBDD) (Pont et al., 2019; Petersen et al., 2006).

2.2 Growth cycle and plant development of wheat

The growth cycle of the wheat plant is characterized by successive developmental stages defined by organ differentiation. These stages of development are referred to as follows: germination, emergence, tillering, floral initiation or double ridge, terminal spikelet, first node or beginning of stem elongation, boot, spike emergence, anthesis, and maturity are the typical physiological stages (Acevedo et al., 2002). The time when the flag leaf and spikes turn yellow is commonly considered physiological maturity (Hanft and Wych, 1982). The length of each developmental phase is mainly determined by genotype, temperature, day length, and sowing time.

Wheat germination requires a grain water content of 35 to 45 percent by weight (Evans et al., 1975). Germination can occur at temperatures ranging from 4° to 37° C, with 12° to 25° C being the optimum range. When the crop emerges, the seed embryo has three to four leaf primordia, with over half of them already initiated (Hay and Kirby, 1991). During germination, the seminal roots emerge first, followed by the coleoptile, inhibiting the first leaf from emerging. The coleoptile length is limited by seeding depth, which varies by genotype and only marginally increases as seeds are sown deeper (Kirby, 1993).

Just before stem elongation begins, bud differentiation into tillers and tiller appearance has usually ended (Baker and Gallagher, 1983). Tillering is governed by many genetic and environmental factors and does not cease at any single wheat development stage (Longnecker et al., 1993). Many tillers abort before anthesis, and not all tillers generate spikes in wheat (Gallagher and Biscoe, 1978). One and a half fertile tillers per plant is a typical quantity under optimal conditions. In cereals, tillering is particularly important since it can partially or entirely compensate for variances in plant number after crop establishment and help the crop recover from early frosts (Acevedo et al., 2002).

Tillering is the process through which lateral shoots grow from axillary meristems near the plant root in *Poaceae* species such as wheat (Kondić et al., 2017), and may positively or negatively impact wheat yield depending on the availability of natural resources such as water, light, and nutrients (Elhani et al., 2007). Tillers can account for up to 70% of grain yield. However, up to 60% of tillers can abort and die off (Moeller et al., 2014). The plant population of wheat is directly affected by the growth and development of a single wheat plant. Therefore, tiller composition significantly influences the quality and structure of wheat populations. As a result, the development of productive wheat tillers is essential (Xu et al., 2015).

Tillering is genetically controlled, but also influenced by environmental circumstances like day length and the light fraction within the wheat canopy. The light recipients or phytochromes of the plant regulate the crop architecture based on the light duration and its quality (Evers et al., 2006; Ugarte et al., 2010). Strongly decreasing trends of emerging new tillers at particular cereal row density or leaf area index (Simon and Lemaire, 1987; Lafarge and Hammer, 2002) or wheat canopy (Evers et al., 2006) have been shown. Furthermore, water and temperature of the cultivation environment play a major role in the regulation of the tiller numbers in wheat crops (Richards, 1988; Hyles et al., 2020). Hence, nutrient insufficiency like nitrogen and phosphorous can also affect tiller initiation directly (Rui et al., 2021; Guo et al., 2019). In addition, auxin and cytokinin hormonal balance also regulate tiller emergence and development (Kondić et al., 2017).

Depending on the sowing time and genotype, from emergence to the double ridge can take anywhere from 60 to 150 days. It is influenced by photoperiod and vernalization, which influence the leaf appearance rate (Phyllochron) and the timing of floral differentiation (double ridge) (Acevedo et al., 2002). Cereal development is typically expressed in degree-days (GDD), with 0° or 4°C providing as the base temperature for physiological processes in wheat, as follows: $GDD = [(T_{max} + T_{min})/2] - T_b$, where T_{max} and T_{min} are the maximum, and minimum daily temperatures, respectively, and T_b is the base temperature. The GDD change with the growing stage and allow for a general estimate of when a given growth stage will occur at a specific place (Acevedo et al., 2002).

Wheat responds to vernalization and flowers after a cold season has passed. The two main types of wheat flowering are characterized by their reaction to vernalization (Flood and Halloran, 1986). Spring wheat has a very mild or no reaction to vernalization, and its frost resistance is minimal. Winter wheat has a strong reaction to vernalization and must flower during a period of cold weather. In the early stages of growth, they are resistant to frost (-20 °C); however, frost resistance gradually decreases towards heading and flowering. They are frost-resistant in the early stages of growth (-20 °C). However, this resistance wears off as they approach heading and flowering. Short days at non-vernalizing temperatures between 21° and 16 °C can completely replace the vernalization requirements of winter types (Evans, 1987). For floral induction, spring genotypes need temperatures between 7° and 18 °C for 5 to 15 days, whereas winter genotypes need temperatures between 0° and 7 °C for 30 to 60 days. Vernalization enhanced cell division in winter genotypes, bypassing an inhibitory mechanism at high temperatures (Evans et al., 1993).

After vernalization, genotypes that are photoperiod sensitive require a specific day length in order to flower. Most cultivated wheat species, on the other hand, are quantitative long-day plants (Major and Kiniry, 1991). Floral induction begins once the photoperiod sensitivity period ends, and the reproductive stage begins (double ridge). In those genotypes sensitive to photoperiod, the rate at which the inflorescence develops following induction is likewise influenced by day-length (Stefany, 1993). The shorter the day, the longer the phase is from double ridge to terminal spikelet, increasing the period and number of spikelets per spike. Wheat adaptation occurs at lower degrees of photoperiod sensitivity, so flowering is not appreciably delayed if the day length is less than optimal (Santibañez, 1994). The basic mechanisms of wheat adaptation to varied environments are vernalization and photoperiod (Acevedo et al., 2002).

When the developing apex moves from the vegetative to the reproductive stage, wheat plants have four to eight leaves in the main shoot. Temperatures exceeding 30 °C cause complete floret formation (Saini and Aspinal, 1982). Only about half of these florets reach anthesis; the rest either abort or insufficiently develop before fertilization (Hay and Kirby, 1991).

Terminal spikelet is the stage at which the second dose of nitrogen fertilizer should be applied (Biscoe, 1988) and serves as an indicator for the use of growth regulator herbicides. The rising apex is 4 mm long at this stage, with 7 to 12 leaves in the main shoot (Kirby et al., 1987). Once the terminal spikelet has formed, the stem continues to elongate, and the spike begins to grow. Spike growth occurs between the appearance of the leaf before the flag leaf and ten days after anthesis (Kirby et al., 1987). Each rachis node on the wheat spike contains only one spikelet. Each spikelet includes three to six potentially fertile florets, which self-pollinated in 96% of cases (Martin et al., 1995). During a three- to five-day period, anthesis begins in the central part of the spike and progresses to the basal and apical parts (Peterson, 1965).

2.3 Methods of hybrid breeding

Multistage selection techniques are routinely used in hybrid breeding operations to deal with many potential crossings. The suitable parental lines are identified in the first stage by examining the performance of a large number of lines. In the second step of selection, parental lines are investigated and chosen based on their general combining ability (GCA) effects. Finally, potential hybrid combinations are chosen based on GCA and specific combining ability (SCA) impacts (Gowda et al., 2012).

Chemical hybridizing agents (CHAs)

CHAs are a class of chemicals used in hybrid seed development that produce male sterility and, depending on the mechanism of action and dosage, can sometimes cause female sterility (McRae, 1985). Compared to CMS systems, an efficient CHA enables the creation of a large number of parental combinations to determine germplasm-combining ability (Cisar et al., 2002). Another benefit of CHA is that it can cause male sterility in the female inbred parent by simply spraying a chemical, significantly reducing manufacturing costs. There are quite a few compounds that make male sterility in wheat, but very few of them meet the majority of the criteria (Cisar et al., 2002).

Cytoplasmic male sterility (CMS)

CMS are characterized in plants by mitochondrial DNA rearrangements that result in chimaeric genes and the inability to produce fertile pollen (Horn, 2006). CMS can develop naturally through mutagenesis or interspecific, intraspecific, and intergeneric crosses (Kaul, 2012). CMS lines in cultivated wheat can be created by first crossing common wheat with wild wheat (e.g., *Triticum timopheevii* Zhuk.) or allied species such as Aegilops, Hordeum, and Secale, and then backcrossing to common wheat (Martin et al., 2008). The United States Department of Agriculture received the last CMS hybrid for testing in 1995. The advancement of chemical hybridizing agent technology has resulted in a significant decrease in research activity on cytoplasmic male sterility (CMS) as a hybrid production technique (Cisar et al., 2002).

Genic male sterility systems

Compared to CMS systems, mutations in nuclear-encoded genes, also known as nuclear (NMS) or genic (GMS) male sterility, can significantly increase the range of parental lines. Non-conditional GMS mutations can be used to overcome the restrictions of conditional GMS. However, the maintenance, replication, and selection of pure male-sterile populations, which are necessary for large-scale hybrid seed production, present challenges. Creating breeding lines with the male-sterile mutant locus directly associated with a visual marker is one way to solve the challenge of a large-scale male sterile generation (Melonek et al., 2021).

Genetic modification (GM) systems

Despite the development of various CHA, CMS, and GMS systems in wheat over the last 60 years, each has substantial limitations in either inducing total male sterility in the female inbred parent or F1 fertility restoration under a variety of climatic conditions. The first report on recombinant DNA engineering techniques to construct a wheat fertility control system was published in 1997. A cytotoxic bacterial ribonuclease in the dominant GMS system especially expressed to cause tapetal cell ablation (Block et al., 1997).

Chemically induced GM systems

In recent decades, the search for an ideal CHA has led to the development of several inducible molecular systems in which chemical application can control fertility via the action of a transgene. Because each of these systems needs chemical spraying, fertility management is occasionally compromised by inadequate climatic circumstances such as wind and rain and limited biological application windows. To ensure that the progeny of male-sterile female inbred parents is inherently 100% sterile, conditional male fertility is recommended over conditional male sterility. Although a chemical-based system based on this would be ideal, none has yet been commercialized (Whitford et al., 2013).

Limitations of hybrid breeding in self-pollinating crops

Hybrid seeds are an important production input in agriculture for yield gains; hybrid vigor or heterosis confers on plants tolerance to abiotic and biotic stresses (Duvick, 2004). In self-fertilizing species, such as sorghum (*Sorghum bicolor*), wheat (*Triticum aestivum)* and barley (*Hordeum vulgare* L.), cross-pollination is limited because of the cleistogamous and hermaphroditic nature of the flower, small flower size and relatively low amount of seed production (Yahaya et al., 2020). Thus, the economic production of hybrid seed in predominantly self-pollinating species requires effective techniques like including mechanical emasculation, genetic male sterility, chemical hybridizing agents and genetic transformation to tackle challenges posed by the floral biology of crops (Veerappan et al., 2014).

Wheat is a self-pollinated crop with a closed floral structure that makes it strictly autogamous, which poses challenges in large-scale hybrid-seed production. A number of methods have been proposed to control pollination in the female parental lines of wheat (McRae, 1985). Hand emasculation entails manual removal of anthers or entire stamens from flowers without mutilating the female reproductive organs (Acquaah, 2012) or anther-aspiration technique involves the physical removal of anthers from the flower via a vacuum-suction system (McDonald, 1994). The effective use of this technique requires considerable skill because florets can be damaged easily. According to Kumar and Singh (2005), hand emasculation is relatively more efficient in species with larger flowers e.g., cotton (*Gossypium hirsutum* L.) than in species with smaller flowers and it is only suitable when small quantities of hybrid seeds are required (Agrawal et al., 2004). While this technique eliminates the potential for self-pollination, it is both labor-intensive and cost-intensive.

The use of chemical hybridizing agents (CHAs) for inducing male sterility has long known in wheat hybrid-breeding programs (McRae, 1985). Initially, the CHAs, such as maleic hydrazide, etherel and gibberellins, caused strong phytotoxic effects and generated inadequate levels of male sterility across a range of environments. As such, their commercial use is considered too risky (Whitford et al., 2013). Therefore, the CHAs, such as RH-007 and WL84811, used in Europe, the USA, South Africa and China have been discontinued because of their selective nature and the discovery of toxic residue in the F1 seeds of treated plants (Cisar and Cooper, 2002).

The current generation of CHAs are pollen suppressors (e.g., clofencet (Genesis®), Monsanto). These CHAs are low-risk chemicals, and are relatively non-phytotoxic and nonspecific, allowing the production of high-quality seeds in a large number of genotypes (Chakraborty and Devakumar, 2006). Parodi and Gaju (2009) reported that the application of clofencet at the rates of 3 kg ha^{-1} to 5 kg ha^{-1} caused 50% to 100% pollen sterility in wheat when applied at the tillering stage. Clofencet has found to be more effective in inducing male sterility for large-scale hybrid wheat production than CMS (Liu et al., 2004; Adugna et al., 2006; Parodi and Gaju, 2009). However, the success rate of hybrid seed technology at a commercial scale is low in self-pollinating species because of several factors, including low seed or fruit yields, poor male-sterilization systems and the tedious, time-consuming, labor-intensive and expensive nature of manual emasculation and pollination (Fu et al., 2014).

2.4 Temperature and water requirements of wheat

Wheat is heat-sensitive, and its sensitivity varies according to the phenological stage. High temperatures are more damaging to grain output during reproductive growth than vegetative growth. Heat stress around anthesis produces a reduction in photosynthetic rate, increased respiration, faster leaf senescence, and increased evapotranspiration, all of which result in fewer grains (Bönecke et al., 2020). For every 1 °C increase in temperature, wheat grain filling time is predicted to reduce by 2.8 days, resulting in a 6% loss in wheat grain yield (Asseng et al., 2015; Schittenhelm et al., 2020).

Heat stress is a severe problem in tropical and subtropical regions. The optimal temperature for wheat grain filling ranges from 12 to 22 °C (Barlow et al., 2015). Temperatures exceeding optimal during grain filling in temperate zones, on the other hand, can result in yield loss. For example, an estimated net loss of 4% in wheat output was reported in France between 1980 and 2008, associated with rising temperatures and decreasing precipitation (Bönecke et al., 2020).

Water availability is a great challenge in wheat production system. Water deficiency in central Europe due to the recent drought stress is the most important limiting factor for autumn-sown cereals (Varga et al., 2015; Blum, 2009). Drought combined with heat waves results in extreme weather conditions for wheat yield production and may cause significant yield losses (Jones et al., 2003, Trnka et al., 2004). In addition, shortening the vegetation period due to the increasing temperature not only resulted in potential yield losses but also influenced the water usage of the wheat crops (Olsen and Bindi, 2002). It is proved that water deficiency events before booting and heading stage of wheat crop have more effect on crop phenology than grain yield, while within flowering stage leads to grain yield reduction (Zhang et al., 2013). Drought affects both leaf expansion and photosynthetic performance resulting in less biomass production (Rose et al., 2017). High temperature and water scarcity cause a severe yield loss by decreasing starch accumulation in the grain (Barnabás et al., 2008). The benefits of early sowing time of wheat cultivars to optimize the yield potential in water-limited or semi-arid regions have been proved in several studies (Flohr et al., 2018; Cann et al., 2020).

On the other hand, the rising level of CO_2 in the atmosphere increases the frequency of heat stress days during the wheat growing season and when it is synchronized with flowering or grain filling and developments. In a long-term study among several wheat cultivars in central Europe, it is shown that increasing temperature by ≥31 °C and ≥35 °C in the heading stage results in yield reduction up to 10–22%. These losses can develop to 14–23% when the wheat crops experience drought stress after sowing (Mäkinen et al., 2018). UV light (UV-A and UV-B), along with water, is a critical resource that drives wheat production. The amounts and quality of UV light available for wheat growth influence the development processes and potential productivity of wheat crops (Mina et al., 2019). The elevated UV-B causes negative impacts on growth of wheat crops by reducing plant height, leaf area index, and slowing the photosynthesis activity. Therefore, reducing the crop biomass yield and photosynthesis performance are inevitable incidence due to the light quality. This phenomenon also has impairment on grain formation and its weight by increasing the levels of superoxide radical and hydrogen peroxide resulting in yield production losses through enhancing peroxidation of lipids and electrolyte leakage. UV-B also has a detrimental effect on photosystem II like chlorophyll, electron transport rate, Rubisco cycle, phosphoenolpyruvate carboxylase and malic dehydrogenase in wheat (Kataria et al., 2019; Carolina et al., 2009; Calderini et al., 2008; Agrawal et al., 2004).

The accumulation of aerosols and air pollutants in the atmosphere over time reduces photosynthetically active radiation reception by the leaves and lowers the yield, which has emerged as a significant challenge for agricultural productivity in both developed and developing countries (Mina et al., 2019). Between 25°N and 45°N latitude, aerosols and air pollutants in the atmosphere reduce incoming radiation by 1.4-2.7% per decade (Stanhill and Cohen, 2001). Solar radiation requirements vary depending on growth stage and variety (Acreche et al., 2009). During the vegetative growth stage, low light levels lower biomass and economic yield by affecting source strength, whereas shade during the reproductive growth stage significantly impacts sink capacities, such as spikelet number per spike, grains per spike, and harvest index (Acreche et al., 2009). Wheat yield was reduced by 35% biologically and 46% economically due to low radiation (Mina et al., 2019).

2.5 Importance of sowing time in wheat

Sowing time is an essential agronomic element determining the production of high yielding cereal crops because it regulates the duration and timing of reproductive and vegetative growth stages (Anjum et al., 2021). Appropriate sowing time for various field crops results in a higher economic output without incurring additional costs since it allows varieties to reach their maximum potential (Praveen et al., 2018). The choice of the ideal sowing time also boosts seed evenness and reduces the total length of the growing season by 5-7 days in summer wheat (Butkovskaya and Kozulina, 2021).

Crop sowing dates have adjusted worldwide to suit the local conditions (Ding et al., 2016). According to a recent study, growing wheat as soon as the rainy season begins can reduce the negative effects of climate change while also resulting in high grain yields in the Mediterranean environment. A study in the UK indicated in winter wheat the varieties with earlier flowering time had superiority in performance compare with others with later flowering time (Sheehan et al., 2021; Harkness et al., 2020). The early sowing could cause early flowering time in UK winter wheat could show more tolerance against abiotic and biotic stress which lead better yield performance (Sheehan et al., 2021). It is shown that 3 weeks delay in sowing time (15th of September) causes a significant reduction in numbers of tillers and thus yield losses. It can more than double the losses compared with the optimal sowing date in early September. A noticeable negative correlation ($r=-0.98$, $p<0.05$) between delayed sowing date and number of tillers in fall have been observed. Also, a significant negative correlation has been observed between sowing time and grain filling stage ($r=-0.97$, $p<0.05$). The late sowing date (29th September) resulted in the lowest harvested yield (6 to 6.8 t ha^{-1}) compared with early sowing in mid-September (8th to 15th September), which was about 7.5 to 8.5 t ha^{-1} in different locations (Klepeckas et al., 2020). An American study reported that earlier sowing in wheat on 10 November could decrease the number of tillers, when in tillering stage, the sum of temperature was over 1000 °C (Scott et al., 2019). According to the experimental result from Denmark, different sowing times can also regulate the weed infestation in wheat production system. It is indicated that sowing time has a direct effect on weed biomass and wheat yield. The highest wheat yield was achieved by normal sowing time (mid-September) only in the case of weed absence or a few infestations. However, the second experiment revealed that weed biomass can also be higher in early sowing time than the late sowing time, which causes overestimation or underestimation of the wheat potential yield (Rasmussen, 2004).

Hunt et al. (2019) in his study based on early sowing in wheat combined with slower-developing wheat cultivars, reported the increased yields potential under climate change scenarios. When the initial soil water is suitable in south Australia, sowing two weeks earlier is an efficient climate change adaptation approach (Ding et al., 2016). To maximize grain yield potential, wheat varieties should sow according to their relative maturities (determined by their reaction to vernalization and photoperiod) so that flowering occurs during the optimal window. Wheat varieties that respond to vernalization (winter types) can sow early and will remain vegetative until their vernalization requirement is met. This delays reproductive development, allowing flowering to coincide with favorable seasonal conditions. Wheat varieties that respond differently to vernalization and photoperiod can provide more flexibility in the sowing schedule. Achieving proper wheat phenology by matching sowing time and variety is crucial to maximizing yield potential and is low-cost when compared to other agronomic management strategies (Harris et al., 2016).

Early sowing (on 5th or 15th of November) contributes to increased yield because of extended growth periods compared with delayed sowing on 25th of November under cultivation climate in India (Praveen et al., 2018). Due to the cold, late planted (25th of November) wheat grows slowly, resulting in poor germination, fewer crop stands, and poor grain quality, although the air temperature in India during the winter generally doesn't decrease more than 5 degrees centigrade and the freezing duration cannot exceed more than 2 days but this effect can be also visible under temperate climate condition (Anjum et al., 2021).

Darwinkel et al. (1977) reported that delaying the sowing date at 3 to 4 weeks interval from end of September to beginning or mid of November or December causes a reduction in grain yield. This drop is driven by fewer grains per ear and reduced grain weight. The number of ears is positively affected by seed rate, while the number of grains per ear and grain weight are negatively affected. Seed rate did not affect grain production with early sowing due to mutual compensating of yield component variations. A higher seed rate raised the number of ears so much with late sowing that a higher grain yield reached. They also demonstrated that the time of sowing had an effect on the pattern of tillering. The majority of tillers emerged in autumn and winter with early sowing, whereas late-sown wheat tillered in spring. Furthermore, the early-sown wheat harvest was dominated by ears from early tillers, whereas the late-sown wheat crop was dominated by ears from late-formed tillers (Darwinkel et al., 1977).

A later sowing date can boost wheat grain yields and assist winter wheat to adapt to the warmer environment from Dickens to Alliance in Nebraska (Weiss et al., 2003). Early sowing of wheat causes leaf rust illnesses in the Sindh region, and the optimum sowing date is the first week of November (Channa et al., 2016). The observed data on the Loess Plateau suggest that wheat sowing has delayed by 1.2 days per decade (He et al., 2015). Delaying sowing from

November 20th onwards affects grain output in Pakistan due to severe cold during the vegetative period and high heat during the reproductive stages (Ali et al., 2004). This phenomenon is also proved from northern to southern Europe including Germany, Denmark, Czech Republic, France, etc (Mäkinen et al., 2018). According to the database obtained from 991 cultivars in Europe (including winter wheat, spring wheat, and durum wheat) by delaying sowing time when the wheat crops confronting encountered frost (<-15°C) most of the cultivars suffered markedly from frost and experienced the yield reduction of 10 to 30% (Mäkinen et al., 2018). The result from England showed a decreasing yield for winter wheat by delayed sowing time (after mid-September), which was on average about 0-35% per day. A similar trend of yield losses (0-43% per day) has been observed in winter barley by delayed sowing time (Green et al., 1985). In Poland, long-term study showed that delayed sowing time significantly decreased the potential yield of wheat cultivars by 4.5 (1986-2003) to 2.5 (2008-2013) percent (Oleksiak, 2014). In line with these results also in Iran considering five different sowing times (i.e., 31th October, 15th and 30th November, 15th and 30th December), the highest potential yield of 10.1 t/ha was achieved by early sowing on 15th of November, while delayed sowing (30th of December) meant the wheat yield was at the lowest level of 6.1 t/ha (Lak et al., 2013).

Sowing time can be used also for regulating wheat root extension into the soil and helping for better crop establishment and nutrient uptakes. Several studies indicated that early sowing dates of winter wheat can be an essential tool to prevent the nitrogen leaching as the greater root development of the wheat crops in autumn helps to increase the nitrogen uptake by the crop compared with normal or delayed sowing time (Thorup-Kristensen et al., 2009; Knudsen et al., 2012; Myrbeck et al., 2012). It is also proved that sowing time as well as mean temperature and vegetative period strongly regulated the rooting depth potential of wheat cultivars (Kirkegaard and Lilley, 2007). A significant rooting depth of wheat crops up to 1 meter down into the soil has been observed by sowing the cultivars in September compared with delayed sowing time in December (Barraclough and Leigh, 1984). In line with this result, Rasmussen et al. (2016) proved that early sowing time of wheat cultivars provides deeper roots and higher root masses during autumn compared with the normal (end-September) or late sowing time (mid-October).

2.6 State of the art of wheat hybrid breeding and cultivation

Hybrid crop cultivars have been widely utilized to increase crop output and yield in the face of a range of environmental problems, such as droughts and poor irrigation (Gupta et al., 2019). Adopting lines from different target environments has been recommended for boosting genetic diversity in pools. However, this technique is hampered by several needs for vernalization, photoperiod, quality, and frost resistance (Koekemoer et al., 2011).

The primary goal of hybrid breeding is to apply heterosis consistently (Melchinger, 1999). Small-scale European trials of winter wheat hybrids documented between 1934 and 1976 imply that heterosis of 30% or higher is achievable (Cisar et al., 2002).

In a study with wheat hybrids under the growing conditions in Germany it was found that the increase in output of the hybrids could be attributed to higher kernel weight rather than an increase in grain number per m^2. When comparing quality classes, hybrids produced more grain and higher average protein output. Hybrid cultivars are commonly associated with increased stress tolerance, which is occasionally explained by stronger root growth (Prey et al., 2019).

It is helpful to explain the concept of hybrid yield advantage when comparing hybrid versus cultivar performance. The relationship between hybrid advantage and expected or realized return on investment in hybrid seed changes according to the wheat commodity price. According to some studies, an economic threshold for transitioning from cultivars to hybrids requires a hybrid yield advantage of 0.65 to 1.0 t/ha, with a return-on-investment of 1.5 to 2.0 t/ha (Cisar et al., 2002).

Despite early failures, hybrid wheat cultivars were commercialized in Europe and the United States in the 1990s, while hybrid wheat research in China began in the late 1980s (Anjum et al., 2021). Europe was the most important hybrid wheat-growing region in 2010, with over 160,000 hectares in France and over 25,000 hectares in Germany (Longin et al., 2012; Gowda et al., 2012).

Heterosis performance in wheat

Plant breeders exploit heterosis as an effective genetic strategy to increase yield and stress resistance in wheat (Singh et al., 2015). Freeman reported heterosis in wheat for the first time in 1919, where the F1 generation showed increased plant height when compared with their parents (Freeman, 1919). Breeders estimated heterosis in wheat by observing progeny traits. These were often influenced by factors such as genetic relation of the parents and environmental conditions (Nie et al., 2019). Morphological observations also cost a lot of labor force and money. Therefore, some breeders have used the analysis of combining ability (Bhullar et al., 1979; Sharma et al., 1991), and the heterosis group division (Liu et al., 1999; Shieh and Thseng, 2002) to improve the breeding efficiency of strong heterosis combination.

Heterosis is the phenomenon that a hybrid outperforms its two parents (Birchler et al., 2006). It refers to the heterozygote produced by hybridization between two or more parents with different genetic bases. Hybrids can be superior to parents in terms of yield, growth rate, viability or disease resistance (Hochholdinger and Hoecker, 2007). The performance of the hybrids estimated in terms of the percentage increase or decrease of their performance over the mid-parent (heterosis) and better parent (heterobeltiosis) (Inamullah et al., 2006). There are three hypotheses to explain the genetic basis of heterosis: dominance (Jones, 1917), overdominance (East, 1936) and epistasis (Powers, 1944). The additive, the dominance and all four epistatic polygenic effects control hybrid performance, whereas mid-parent heterosis (MPH) is not affected by the additive effect because the additive effect does not contribute to heterosis (Jiang et al., 2017).

Maize is the most successful example for the utilization of heterosis in crops to improve agricultural production (Hochholdinger and Baldauf, 2018). Thus, hybrid breeding is well established in many outcrossing species like e.g., maize but is still under development in wheat (Gupta et al., 2019). A mid-parent heterosis for grain yield of approximately 10% has been reported for hybrid bread and durum wheat (Gowda et al., 2010; Thorwarth et al., 2018). In another study mid-parent heterosis (MPH) for wheat grain yield averaged 0.02 t ha^{-1} (0.5%) and varied from −15.33% to 14.13% (Dreisigacker et al., 2005). In a further wheat study, the mid-parent value showed a negative correlation with MPH but positively correlated with the hybrid performance (Boeven et al., 2020).

Both positive and negative heterosis is useful depending on the breeding objectives. Generally, positive heterosis desired in the selection for yield and its components, whereas negative heterosis desired for early cycling and low plant height (Lamkey and Edwards, 1999; Alam et al., 2004). Additive and non-additive effects have been reported for grain yield and its components in wheat in studies throughout the world (Krystkowiak et al., 2009). Previous studies on wheat have reported extreme positive values of heterobeltiosis and heterosis (48 and 60%, respectively) for grain yield (Hussain et al., 2007; Bertan et al., 2009; Gami et al., 2011). Phenotypic bases of heterosis have a large variability. In hybrid individuals, not all traits are necessarily heterotic (Kaeppler, 2011). In convergence, it is acknowledged that there is no correlation in levels of heterosis for different traits (Longin et al., 2013; Huang et al., 2015). For example, a hybrid individual might show heterosis in yield and height, but not root angle, and the amount of heterosis for yield and height may differ (Labroo et al., 2021).

Furthermore, it was shown that there is a negative heterosis value in protein content of wheat grain, which might be explained by the negative correlation between grain yield and protein content (Oury and Godin, 2007; Thorwarth et al., 2019; Boeven and Longin, 2019). The degree of heterosis can also depend on environment. Maize hybrids usually show more heterosis in stressful than non-stressful environments, even as overall performance is decreased (Duvick et al., 2004). A positive heterosis for days to flowering is equivalent to negative heterosis for speed of development. A plant, which flowers later, would have a more positive value for days to flowering, but it would have a less positive value for speed of development since it matures more slowly (Falconer and Mackay, 1996). Therefore, a progeny that flowers later than its mid-parent would show positive heterosis for days to flowering, but negative heterosis for speed of development even though the character measured (when the progeny flowers) is identical (Labroo et al., 2021).

Heterosis effect used in breeding of open-pollinated plants, such as maize or rye, also focused on self-pollinated plants, including wheat (Liu et al., 1999; Pomaj, 2002; Weißmann and Weißmann, 2002). Even though the yield heterosis level in wheat cannot be compared with those found in allogamous species such as maize, the agronomic value of wheat hybrids appears to be promising (Oury et al., 2000). Although, the production of hybrids has been greatly enhanced by the discovery of effective chemical hybridizing agents (Pickett and Galwey, 1997). The knowledge about hybrid performance, the relative importance of general (GCA) and specific (SCA) combining ability, and the genetic background of parental materials for maximum exploitation of heterosis in wheat, remains limited (Dreisigacker et al., 2005).

High heterosis emerged when the source populations have a high frequency of genes with partial or complete dominance and maximum differences in gene frequencies of over dominant loci (Hallauer et al., 1988). Consequently, for an optimum exploitation of heterosis, parents should derive from genetically divergent germplasm pools, commonly referred to as heterotic groups (Melchinger and Gumber, 1998) which are not available or easily discernable in wheat because of breeding history. The main goal of hybrid wheat breeding is the identification of parents with high specific combining ability (SCA) for technological quality and agronomic traits. Such data facilitate the choice of pairs of parental genotypes with a high probability of heterosis in their F1 progeny (Krystkowiak et al., 2009). In the case of self-pollinated crops these methods require a large number of manual crossings, which make them time-consuming and expensive (Shen et al., 2006).

2.7 Yield stability of wheat

The principal goal of plant breeding projects is to identify genotypes with high grain yield and yield stability (Milioli et al., 2018). Trait stability, particularly yield and quality traits, is a prerequisite for high-yielding crops. These traits need to be consistent from year to year across various environments. Farmers, in general, prefer guaranteed minimum productivity to gamble on high-yield crops with the risk of very low production. On a global scale, it is also preferable to have yield stability and the resulting influence on markets (Hawkesford et al., 2013).

Future climate change and increasing climate diversity have been scientifically proven for German field situations. On the one hand, there has been an increase in demand for wheat with a stable yield and adaptation to climate change outside of Germany. On the other hand, recent German research shows that farmers are particularly interested in increasing the yield stability of wheat cultivars (Macholdt and Honermeier, 2017).

2.7.1 Concepts of yield stability

Yield stability has two concepts: static and dynamic. The concept of static stability refers to genotypes that yield similarly in all environments and are hence better yielding in unfavorable conditions (Weedon and Finckh, 2019). Stability in the dynamic sense indicates that the genotype responds positively to improvements in environmental variables and can perform above the mean in diverse locations. Plant breeders and farmers are interested in this behavior (Sabaghnia et al., 2015).

Static stability is defined by values such as environmental variance (S^2i) and coefficient of variation (CV %). In contrast, dynamic stability is defined by parameters such as Plaisted’s GE variance component, regression coefficient (bi), Pinthu’s coefficient of determination (R^2), variance of regression deviations (S^2di), Wricke’s ecovalence (W_i), Shukla’s stability variance (σ_i^2), heterogeneity variance (HV%), and incomplete correlation (IC%) (Ramla et al., 2016).

A recent study found positive correlations between Wricke's ecovalence (W_i) (1962) and Eberhart and Russell (bi, S^2di) (1966), two crucial indicators of dynamic stability (Milioli et al., 2018).

Lin et al. (1986) divided the yield stability of crops/genotypes into three concepts: 1) a genotype is considered stable if its among-environment variance is negligible. Becker and Léon (1988) defined this stability as static or biological. A stable genotype maintains its performance regardless of environmental changes. This concept of stability can be applied to quality traits, disease resistance, or stress characteristics like winter hardiness. The coefficient of variability (CV_i) utilized by Francis and Kannenburg (1978) for each genotype as a stability parameter and the genotypic variations across environments are the parameters used to define this concept of stability (Si^2).

2) A genotype is considered stable if its response to environmental effects is consistent with the mean response of all genotypes in the trial. Becker and Léon (1988) classified this stability as dynamic or agronomic. A stable genotype has no deviations from the general response to environments, allowing for a predictable response. This type of stability can be measured using a regression coefficient (bi) (Finlay and Wilkinson, 1963) and Shukla’s (1972) stability variance (i^2).

3) A genotype is considered stable if the residual mean square from the regression model on the environmental index is small. The environmental index shows the mean yield of all the genotypes in each location minus the total mean of all the genotypes in all locations. This type of stability is also categorized as dynamic or agronomic stability, according to Becker and Léon (1988). The methods of Eberhart and Russell (1966), and Perkins and Jinks (1968) referred to this type of stability. According to Becker and Leon (1988), all stability approaches based on

quantifying genotype-environment interactions (GEI) effects fall under the dynamic concept of stability. This includes the procedures for partitioning the GEI of Wricke’s (1962) ecovalence and Shukla’s (1972) stability of variance, procedures using the regression approach such as proposed by Finlay and Wilkinson (1963), Eberhart and Russell (1966) and Perkins and Jinks (1968) as well as non-parametric stability analyses.

2.7.2 Methods of yield stability analyses

Numerous yield stability analysis methods have already been used. One of them is the joint regression method which performs regression analyses of either phenotypic values or interactions on environmental indicators, which is the most popular method for assessing stability. Yates and Cochran (1938) first outlined these methods, and the modified version used by Finaly and Wilkinson (1963) and Eberhart and Russell (1966). In addition, Finlay and Wilkinson (1963) defined stability as the linear relationship of the genotype yield over environments by the regression coefficient (bi), where a genotype with bi=1 was regarded as stable. Eberhart and Russell (1966) expanded on the concept by incorporating the regression deviation mean squares (S di) as a measure of stability. The mean performance, the slope of the regression line (bi), and the sum of squares deviation from regression (S^2di) are three empirical parameters that contribute to genotype stability. As a result, a stable genotype will have a high mean yield over the environment, a unit regression coefficient (b=l), and a deviation from regression equal to zero (S^2di).

Tai (1971) also proposed a two-stability parameter method similar to Eberhart and Russell's (1966). When the environmental index is considered to be random, environmental effects (αi) and deviation from the linear response (λi) can be considered as specific forms of the regression parameters (bi) and (S^2 di) (Lin et al., 1986). Tai's (1971) model is based on the structural relationship analysis principle, in which the genotype-environment interaction effect of variety partitioned into two components. They are the linear response to environmental effects, as evaluated by the (αi) statistic and the deviation from the linear response, as assessed by the (λi) statistic.

Wricke (1962) proposed using genotype-environment interactions (GEI) as a stability measure for each genotype, which he termed ecovalence (Wi). This stability parameter considers genotypes with the lowest ecovalence (Wi2) values to be stable. Furthermore, Shukla (1972) proposed an unbiased estimate based on genotype stability variance (σ2 i) and a method to test the significance of the (σ2 i) for evaluating genotype stability. For each genotype, a comparison of (σ2 i) with (σ0 2) (pooled error from ANOVA) is performed. Genotypes with a significant F value of σ2 i regarded as unstable. A further method was developed by Francis and Kannenberg (1978) who employed the coefficient of variation (CVi) and the environmental variance (S2i). According to Francis and Kannenberg (1978), genotypes with low CVi and low S 2 i are considered stable (Lin et al., 1986).

2.7.3 Previous studies on yield stability in wheat

In a Turkish study, nine stability parameters for durum wheat grain yield were estimated using Eberhart and Russell's (1966) slope value (bi) and deviation from regression (S^2 di), Pinthus' (1973) coefficients of determination (R^2), Wricke's (1962) ecovalance (Wi 2), Shukla's (1972) stability variance (σ2 i), Francis and Kannenberg's (1978) coefficient of variability (CVi) and genotypic variance (S 2 i), Tai's (1971) environmental effects (αi) and deviation from the linear response (λi). Yilmaz-98, Cakmak-79, Kiziltan-91, Selcuklu-97, and C-1252 were the more stable cultivars, with 9, 8, 6, 6, 6 out of the total of 9 stability statistics used. Yilmaz-98 and Cakmak-79 were the most stable cultivars among these. The genotype means yield (-x) was significantly positively correlated to the regression coefficient (bi), environmental variance, and genotype to the environmental effects (αi), indicating that higher grain yielding genotypes had higher values bi, S^2i. In addition, αi, S^2i Wi 2, CVi and bi significantly correlated, indicating that they measured similar stability aspects (Akcura et al., 2006).

In Egypt, stability analyses were performed on ten wheat varieties across eight environments using six parametric stability statistics (Xi, bi, S^2di, Ri, Wi 2 and S^2i). Stability analyses for grain yield of wheat genotypes revealed that the genotypes Bohouth 8, Cham 8, L-R 40, Sids I, Cham 10 and Sahel I were more stable than others, expressed in 4, 4, 3, 3, 3 and 3 out of all six stability statistics used, respectively. Thus, these genotypes were suggested as being more stable than the others (Abd El-Shafi et al., 2014).

In a German study, Mühleisen et al. (2014) re-analyzed three published data sets of wheat, barley, and triticale to investigate the yield stability of hybrids versus lines. The stability variance was interpreted analogously to the stability variance described by Shukla (1972), with the difference that the above-described stability variance is specific for genotypic groups, whereas Shukla's stability variance is specific for individual genotypes. The yield stability of the hybrid group compared to that of the group of inbred lines with stability variance.

Mühleisen et al. (2014) reported that hybrids had significantly ($P<0.05$) higher yield stability than lines for barley, triticale and wheat. The improved yield stability of hybrids over lines is a significant advancement and makes it easier to manage the increased abiotic stress anticipated from the projected climate change. Liu et al. (2017) evaluated yield stability based on phenotypic data from five series of official winter wheat registration trials in Germany, each including 119—132 genotypes and up to 50 environments. The yield stability parameters that were estimated by Piepho's approach in 1999 and Shukla's yield stability variance (Shukla, 1972). The results of this study showed that hybrids outperformed lines for grain yield but not for yield stability.

Stability for grain yield performance was studied in twelve wheat genotypes at various locations having different agro-climatic conditions in Sindh province of Pakistan over two years. A joint regression analysis was applied to grain yield data to estimate the stability parameters, including regression coefficient (b), Se. (b) and deviation from regression coefficients (S2d) for each genotype. Genotype MSH-14 produced the highest mean yield (5090 kg/ha) in all environments averaged for two years and had regression coefficient (b) close to unity (0.86) and S2d close to zero (0.80). This indicated wide adaptation and stability of the performance of MSH-14 in all environments. Other high-yielding genotypes MSH-03 and MSH-05 ranked two and third, showing regression coefficient (b=0.78 and 0.69 respectively) and deviation from regression (S2d= 1.076 and 1.29 respectively), indicating specific adaptability of these genotypes to harsh (unfavorable) environments (Arain et al., 2011).

3 Material and methods

3.1 Site description

3.1.1 Experimental station Giessen (GI), "Weilburger Grenze"

The experimental station GI is located 50 km north of Frankfurt (50° 60' 12" north, 8 °65' 32" east) and 158m above sea level (Figure 1).

Figure 1: Plot designation of wheat trial, "Weilburger Grenze" Giessen, 2018. (photo: Yavar Vaziritabar).

The soil in GI is classified as a Eutric Fluvic Gleyic Cambisol (WRB, 2015). The topsoil (0-30 cm) is characterized by silty clay texture with a clay content of 39-49%, silt content of 40-58%, an organic carbon content of ca. 1.8%, a usable field capacity (0-100 cm) of 123 mm, and pH value of 6.0-7.1. Table 1 shows the soil nutrients in GI station from 2012 to 2019.

Table 1: Dynamics of N (NO_3^-), K_{CAL}, P_{CAL}, Mg concentrations, and pH value in the soil of the station "Weilburger Grenze" Giessen according to soil depth from 2012 to 2019.

Soil nutrients	Depth (cm)	2012	2013	2014	2015	2016	2017	2018	2019
N (kg NO_3^- N/ha)	0-30	-	12.6	12.1	13.4	10.2	37.1	3.4	17
	30-60	-	14.8	12.1	13.3	11.6	39.5	7.6	22.7
	60-90	-	14.1	12.6	13.4	8.4	24.5	16.8	21.4
	0-90	-	41.5	36.5	40.1	30.3	101.1	27.9	61
K_{CAL} (mg/100 g)	0-30	5.2	9.9	3.9	15.3	4.1	11.7	12.4	100.8
P_{CAL} (mg/100 g)	0-30	10.1	14.6	11.7	18.3	11.4	10.6	4.0	65.3
Mg (mg/100 g)	0-30	-	12.0	9.5	17.5	23.1	28.2	19.2	34.6
pH	0-30	6.6	6.3	6.8	6.4	6.5	7.1	6.0	6.4

The nitrogen fertilizer (nitrate, 270 g kg^{-1}) applied three times, with 165 to 200 kg N/ha per year (Table 1). Phosphorus and potassium were applied as superphosphate and KCl with a total of 60 kg P/ha and 164 kg K/ha yearly. The fertilizers applied in the combination of soil tillage during the autumn prior to sowing time.

Experimental design

The field experiment consisted of two main factors: (A) sowing time and (B) cultivars (hybrids versus lines), all of which are arranged in a randomized complete block design with four field replications in 2012 to 2016. Due to extraordinary climate conditions (wind and hail), the number of sowing times was reduced to two or one in 2017, 2018, and 2019 (Table 2). The plot size (at sowing) was 10 m x 1.5 m (15 m²) and the plot area (at harvest) was 7 m x 1.5 m (10.5 m²). The row space of wheat plants was 17cm and the sowing method was drilling and done by plot seed drill device machine. The wheat was harvested, separately in the plots of each sowing, at the time of full ripeness with a plot harvester.

Table 2: Sowing time, harvesting date and mineral N fertilization of winter wheat in field experiments in Giessen 2012 – 2019.

Factor		2012	2013	2014	2015	2016	2017	2018	2019
Sowing time	1	29/9/11	2/10/12	2/10/13	1/10/14	8/10/15	7/10/16	19/10/17	28/9/18
	2	1/10/11	16/10/12	16/10/13	21/10/14	26/10/15	31/10/16	-	19/10/18
	3	28/10/11	1/11/12	1/11/13	31/10/14	6/11/15	-	-	-
Harvest date	1	10/8/12	15/8/13	19/8/14	2/8/15	8/8/16	14/8/17	30/7/18	31/7/19
Fertilization kg N/ha and application date	1	70	60	70	70	70	80	80	70
		7/3/12	5/2/13	28/2/14	9/3/15	11/3/16	15/3/17	22/3/18	27/2/19
	2	50	70	60	60	70	80	60	60
		19/4/12	4/5/13	2/4/14	14/4/15	25/4/16	26/4/17	27/4/18	12/4/19
	3	50	60	60	50	30	40	25	40
		14/5/12	3/6/13	6/6/14	27/5/15	27/5/16	17/5/17	18/5/18	29/5/19

3.1.2 Experimental station Gross Gerau (GG)

Gross Gerau is an experimental station located in the upper Rhine valley (49 o 45´N and 8° 29' E) 90m above sea level. From the north the Main River flows, whereas from the west the Rhine River runs along, and to the east the Odenwald Mountains are located. The soil is characterized as sandy high flood sediments. The top layer of the soil contains sandy soil (Boden viewer Hessen), organic carbon content of ca. (0-30 cm) is about 1.5 %. It has a limited buffering capacity and slightly humic soil. As a result, the consistency of the soils varies from loam to loamy sand. The soil pH is 6.0 to 6.9, and the soil points are 20 to 25. Table 3 shows the soil properties in GG station from 2012 to 2019.

Table 3: Dynamics of N (NO_3^-), K_{CAL}, P_{CAL}, Mg concentrations and pH value of the soil depending on the soil depth in Gross Gerau station from 2012 to 2019.

Soil nutrients	Depth (cm)	2012	2013	2014	2015	2016	2017	2018	2019
N (kg NO_3^- N/ha)	0-30	3	2	2	2	5	13	4	5
	30-60	2	16	1	4	2	11	3	4
	60-90	6	17	5	9	5	-	7	9
	0-90	11	35	8	15	12	24	14	18
K_{CAL} (mg/100 g)	0-30	12	15	22	15	22	21	16	16
P_{CAL} (mg/100 g)	0-30	15	-	8	12	24	21	22	23
Mg (mg/100 g)	0-30	4	4	2	4	17	2	2	2
pH	0-30	6.8	6	5.5	6	6.7	6.5	6.2	6.5

Experimental design

The field experiment consisted of two main factors: (A) sowing time and (B) cultivars (hybrids versus lines), all of which are arranged in a randomized complete block design with four field replications, except 2017 where just three field replications were implemented. During the period from 2012 to 2016, the trial experienced three different sowing times, the number of sowing times reduced to two or one in 2017, 2018, and 2019 (Table 4).

The reduction of sowing times was caused by unfavorable climate conditions. The harvest date in GG was earlier than in GI because of warmer climate conditions (Table 4). The plot size (at sowing) was 10 m x 1.5 m (15 m²) and the plot area (at harvest) was 7 m x 1.5 m (10.5 m²). The row space of the wheat plants was 17cm and the sowing method was drilling which was done by a plot seed drill device machine. The wheat was harvested, separately in the plots of each sowing, at the time of full ripeness with a plot harvester. The investigation in experimental station GG was carried out for eight years, from 2012 to 2019.

Table 4: Sowing time, harvesting date and mineral N fertilization of winter wheat in Gross Gerau 2012-2019.

Factor		2012	2013	2014	2015	2016	2017	2018	2019
Sowing time	1	21/9/11	28/9/12	25/9/13	6/10/14	12/10/15	11/10/16	18/10/17	9/10/18
	2	4/10/11	12/10/12	9/10/13	20/10/14	26/10/15	2/11/16	-	31/10/18
	3	14/10/11	25/10/12	22/10/13	3/11/14	9/11/15	-	-	-
Harvest date	1	19/7/12	23/7/13	17/7/14	16/7/15	26/7/16	31/7/17	5/7/18	23/7/19
Mineral N fertilization kg N/ha and application date	1	70	70	70	40	70	80	70	65
		1/3/12	6/3/13	27/2/14	5/3/15	14/3/16	15/3/17	15/3/18	26/3/19
	2	60	60	60	50	50	80	60	45
		16/4/12	26/4/13	7/4/14	14/4/15	14/4/16	26/4/17	24/4/18	25/4/19
	3	-	50	50	70	60	30	50	50
			3/6/13	6/5/14	15/5/15	9/5/16	15/5/17	7/5/18	9/5/19

3.1.3 Experimental station Rauischholzhausen (RH)

The experimental station RH is located near Marburg (50° 75'80" north, 8° 88' 40" east) with a ground elevation of 200-220 m above sea level. The soil is characterized as Haplic Luvisol which is characterized by a texture of 16-18% clay, 69% silt and 9% sand. The organic carbon content of the soil is about 1.4% (0-30 cm) and pH values (0-30 cm) varied from 6.1 – 6.6. Table 5 shows the soil properties in RH station from 2016 to 2018.

Table 5: Dynamics of N (NO_3^-), K_{CAL}, P_{CAL}, Mg concentrations, and pH value in Rauischholzhausen station according to soil depth from 2016 to 2018.

Soil nutrients	Depth (cm)	2016	2017	2018
N (kg NO_3^- N/ha)	0-30	17	15.7	3.2
	30-60	8	10.9	3.5
	60-90	9	12.7	2.9
	0-90	34	39.3	9.6
K_{CAL} (mg/100 g)	0-30	20.45	17.15	15.5
P_{CAL} (mg/100 g)	0-30	9.83	10.19	23.14
pH	0-30	6.25	6.13	6.8

Experimental design

The field experiment consisted of two main factors: (A) sowing time and (B) cultivars (hybrids versus lines), all of which are arranged in a randomized complete block design with four field replications. The investigation in RH station lasted three years, from 2016 to 2018. The trial had two sowing times in 2016 and 2017 and only one sowing time in 2018. The plot size at sowing was 10 m x 1.5 m (15 m²) and the plot area at harvest was 7 m x 1.5 m (10.5 m²). The row space of the wheat which was drilled by a plot seed drill machine was 17 cm. The wheat was harvested, separately in the plots of each sowing, at the time of full ripeness with a plot harvester. Table 6 shows the amount of nitrogen fertilizer used in Rauischholzhausen (kg N/ha) and its application date.

Table 6: Sowing time, harvesting date and mineral N fertilization of winter wheat in Rauischholzhausen 2016 – 2018.

Factor		2016	2017	2018
Sowing time	1	11/10/15	12/10/16	19/10/17
	2	7/11/15	27/10/16	-
Harvest date	1	16/7/16	17/8/17	3/8/18
Mineral N fertilization kg N/ha and application date	1	80 14/3/16	80 13/3/17	60 6/3/18
	2	40 13/4/16	60 10/4/17	70 24/4/18
	3	60 31/5/16	60 9/5/2017	-

3.2 Characteristics of the cultivars used

The selected cultivars for the experiment are summarized in Table 7. The oldest cultivar used in this experiment was Ritmo, with the approval date in 1993. Conversely, Hymalaya was the most recently (2018) approved cultivar with the A class of baking quality. Most of the selected hybrid cultivars in this experiment was grouped in the B baking quality class. The line cultivars tested in the experiments included all baking quality classes of A, B, C and C_K

Table 7: Characteristics of the wheat cultivars used for the study, L= line, H=hybrid.

Cultivars	ID	Breeder	Year of approval	Baking Quality	Line/ Hybrid
Ambello	WW 4814	R2n S.A.S.	2010	A	L
Bonanza	WW 4727	Borries-Eckendorf GmbH	2015	B	L
Boxer	WW 4426	Ackermann Saatzucht GmbH	2013	C	L
Cubus	WW 2787	KWS Saat SE & Co. KGaA	2002	A	L
Dekan	WW 2486	KWS Saat SE & Co. KGaA	1999	B	L
Egoist	WW 4123	Borries-Eckendorf GmbH	2011	B	L
Faustus	WW 4734	Dr. Hermann Strube	2015	B	L
Genius	WW 3953	NORDSAAT Saatzucht GmbH	2010	E	L
Hybery	-	ASUR Plant Breeding	2010	B	H
Hybred	WW 2932	Hybritech Europe SNC	2003	B	H
Hycory	WW 3521	Petersen Saatzucht Lundsgaard	2007	B	H
Hyena	WW 5343	NORDSAAT Saatzucht GmbH	2018	B	H
Hyland	WW 3648	NORDSAAT Saatzucht GmbH	2009	B	H
Hylux	WW 5070	ASUR Plant Breeding	2012	C	H
Hymack	WW 4170	ASUR Plant Breeding	2007	B	H
Hymalaya	WW5357	NORDSAAT Saatzucht GmbH	2018	A	H
Hystar	WW 4499	ASUR Plant Breeding	2007	B	H
Hyvento	WW 4760	NORDSAAT Saatzucht GmbH	2016	A	H
JB Asano	WW 3660	Saatzucht Josef Breun	2008	A	L
KWS Ferrum	WW 4276	KWS Saat SE & Co. KGaA	2012	B	L
Lear	WW 4025	LIMAGRAIN GmbH	2010	C	L
LG Alpha	WW 4893	LIMAGRAIN GmbH	2016	C	H
Linus	WW 3959	R2n S.A.S.	2010	A	L
Meister	WW 3964	R2n S.A.S.	2010	A	L
Opal	WW 4113	Syngenta Seeds	2011	A	L
PZO Pilgrim	WW 4478	Dr. Peter Frank	2004	E	L
Ritmo	WW 1889	LIMAGRAIN Nederland	1993	B	L
Sarmund	WW 4552	Strube research	2014	C	L
Tabasco	WW 3632	Borries-Eckendorf GmbH	2008	C_k	L

Table 8 depicts the tested cultivars in different locations (GI, GG and RH) from 2012 to 2019. The composition of tested cultivars was not identical throughout the different locations and years. The reasons for the variation in the varieties used can be seen in the limited availability of seed and in the topicality of the varieties in the respective years. Nevertheless, the varieties used represent the best performing cultivars of the respective years. In RH, in 2016 and 2017 only line cultivars were cultivated. However, in 2018, the combination of hybrid and line cultivars constituted the tested cultivars (Table 8).

Table 8: List of examined wheat cultivars in respective locations that were used (GI: Giessen, GG: Gross Gerau, RH: Rauischholzhausen) from 2012 to 2019.

Location	GI								GG								RH		
Year	2012	2013	2014	2015	2016	2017	2018	2019	2012	2013	2014	2015	2016	2017	2018	2019	2016	2017	2018
Cultivar																			
Ambello					×														
Bonanza						×	×	×						×	×	×			×
Boxer																	×	×	
Cubus																	×	×	
Dekan																	×	×	
Egoist	×	×	×	×					×	×	×	×	×						
Faustus					×														
Genius																	×	×	
Hybery	×	×	×			×	×	×	×	×	×	×	×	×	×	×			×
Hybred	×	×	×	×					×	×	×	×	×						
Hycory				×															
Hyena								×								×			
Hyland			×	×	×	×						×	×	×					
Hylux					×	×	×							×	×				×
Hymack	×	×		×					×	×	×								
Hymalaya								×								×			
Hystar	×	×	×		×	×			×	×	×	×	×	×					
Hyvento					×	×	×	×						×	×	×			×
JB Asano																	×	×	
KWS Ferrum																	×	×	
Lear	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×			×
LG Alpha							×								×				×
Linus	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×			×
Meister	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×			×
Opal																	×	×	
PZO Pilgrim																	×	×	
Ritmo																	×	×	
Sarmund																	×	×	
Tabasco	×	×	×	×	×	×		×	×	×	×	×	×	×		×			

3.3 Climate conditions

3.3.1 Giessen

Year 2012

The first sowing in Giessen 2011/2012 was on September 29th, followed by the second sowing on October 1st, and the third sowing on October 28th. In November, the experiment saw a cool (3.5 °C) and dry (0.9 mm) weather pattern, followed by three dry months in January, February, and March. The weather in April was also cool (at 6.8 °C) compared to other years. The precipitation amounts were 55.4, 91.1 and 77.5 mm during May, June, and July.

Year 2013

In 2012/2013, the first sowing was on October 2nd. Two days later, on October 4th, there was 8.8 mm of rain. The second sowing period began on October 16th. At sowing time, the soil was wet since a rainfall with 6.4 mm precipitation occurred two days before the second sowing. The subsequent precipitation (9 mm) after sowing happened on October 26th, and directly after the third sowing on November 1st, precipitation (0.6 mm) occurred. The cultivation period was characterized by cold February (1 °C) and March (1 °C) air temperatures and dry winter (January, 17.5 mm; February, 17.3 mm; and March 12.2 mm rainfall). In May, the precipitation was above the average, with 160 mm of rainfall.

Year 2014

The first rainfall (110 mm) in 2013/2014 happened two days after the first sowing on October 4th. The second sowing was on October 16th, and the rain (0.5 mm) coincided with it. The third sowing was on November 1st, with 3.4 mm of precipitation. The air temperature was pleasant, with a wet October (with over 100 mm of rainfall) and a dry March (with 10 mm of precipitation for the whole month). Before harvest in July, the precipitation was around 130 mm.

Year 2015

In 2014/2015, the first sowing was carried out on October 8th, and the trial was confronted with 7.1 mm of rainfall. The second sowing was on October 26th, and the next rainfall occurred on October 29th (1 mm). The third sowing was occurred on November 6th, and the day following, 0.4 mm rainfall was recorded. The air temperature was normal over the cultivation year, with drought stress from April to June.

Year 2016

In 2015/2016, the first sowing was done on October 8th, when the first rain after sowing occurred. The second sowing was on October 26th and on October 27th, and the precipitation was about 0.1 mm. The next precipitation occurred with the third sowing was on November 6th. The growing period was characterized by a winter with a higher average temperature (9.3, 7.5

and 7 °C in October, November and December, respectively) and wet weather in June (116.4 mm) followed by drought stress in July (38.3 mm).

Year 2017

In 2016/2017, the first sowing was done on October 7th. The first precipitation (3.3 mm) recorded on October 10th. The second sowing was on October 31st, and the first precipitation (0.2 mm) after the second sowing was carried out was on the 2nd of November, followed by 0.4 mm rainfall on November 4th and 4.9 mm rainfall on November 5th. The weather conditions in December and January were dry, and the trail experienced a cold winter in January (-1.5 °C). In March, the average air temperature of 14.2 °C and the amount of precipitation in July (109.7 mm) and August (145.6 mm) recorded.

Year 2018

In 2017/2018, only one sowing was implemented on October 19th, followed by precipitation (2.6 mm) in the following days. The mean air temperature in February was about (-0.9 °C), followed by a hot spring and summer. The precipitation in May was about 120 mm; however, the trail experienced a dry season from June to August.

Year 2019

In 2018/2019, the first sowing was performed on September 28th, and the precipitation with 0.8 mm occurred on October 2nd. The second sowing was performed on October 19th, the precipitation with 0.1 mm occurred a few days later, on October 24th. February was a particularly dry month, with precipitations less than 20 mm. In June, an early harvest driven by high air temperatures (which reached 39.6 °C) and less rain (46 mm).

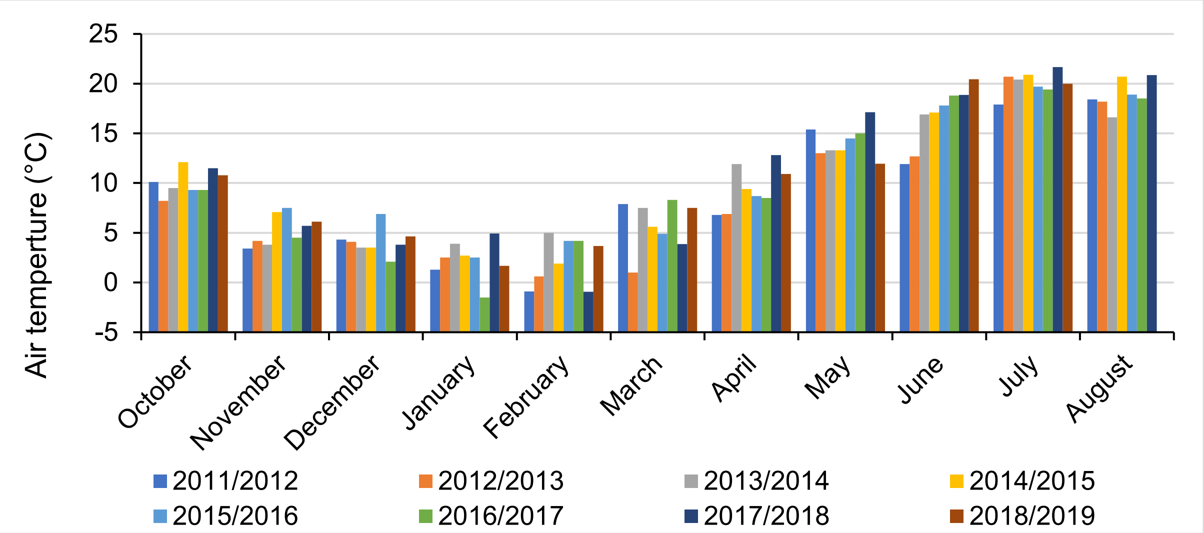

Figure 2: Air temperature (means per month in °C) during the growth cycle of winter wheat, experimental station Giessen 2011-2019.

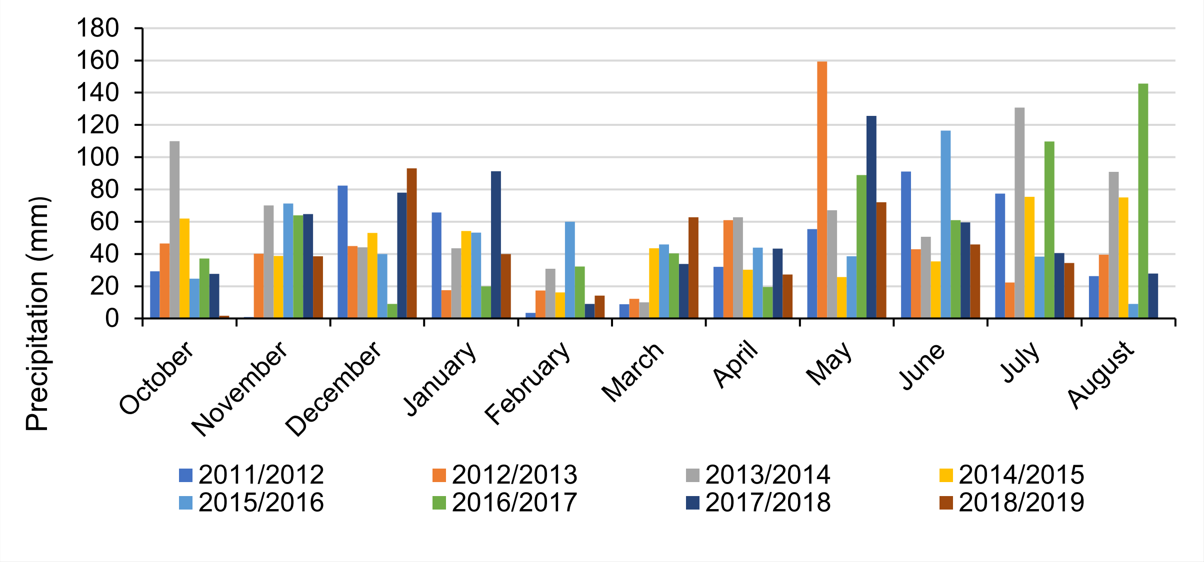

Figure 3: Precipitation sums per month (mm) during the growth cycle of winter wheat, experimental station Giessen, 2011- 2019.

3.3.2 Gross Gerau

Year 2012

In 2011/2012, the first sowing was carried out on September 21st, and the second sowing was on the October 4th. The first precipitation was 6.7 mm on October 6th. The third sowing was on October 14th, followed by the first precipitation (4 mm) on October 18th after the third sowing. In November, the total amount of precipitation was 2.5 mm (Figure 4). In February, the weather was cold (-0.5 °C) and dry, with only 6.8 mm of precipitation. In the following spring, the precipitation was at an average level (April 40 mm and May 76.3 mm). However, in June, it was compensated by 120 mm of precipitation.

Year 2013

In 2012/2013, the first sowing was on September 28th in wet soil due to the previous day's precipitation (2.7 mm), and the subsequent precipitation (0.3 mm) occurred on October 3rd. The second sowing was performed on October 12th, with 4.9 mm precipitation on the same day. The third sowing was carried out on October 25th, and there was precipitation of 12.5 mm on the next day. The winter was dry (Figure 4), followed by a cold spring and a lot of precipitations (138 mm) in May.

Year 2014

In 2013/2014, the first sowing was performed on September 25th. On that day, there was 0.1 mm of precipitation, followed by 0.2 mm the next day. The second sowing was on October 9th, and precipitation (111 mm) fell on that day and the next day. The third sowing was on October 22nd, and the precipitation (0.9 mm) recorded on that day and the next day (4.4 mm). In April, the air temperature was normal, with a temperature of 13.3 °C (Figure 5). The trial irrigated by heavy rain (111 mm) in October. However, precipitation was insufficient (19.2 mm) after overwintering in March, and a dry weather condition followed in April with 30.2 mm precipitation.

Year 2015

In 2014/2015, the first sowing was performed on October 6th, with 11.7 mm of precipitation after sowing. The second sowing was on October 20th, with 5 mm of precipitation following sowing. The third sowing was on November 3rd, with precipitation of 2.5 mm on the same day. In spring, the weather was dry with precipitation of less than 25 mm per month from March to May, while in July the trial experienced a temperature of 22.2 °C on average.

Year 2016

In 2015/2016, the first sowing was performed on October 12th, and precipitation (4.1 mm) was occurred two days later. On 26th of October, 0.1 mm of precipitation fell, followed by 0.1 mm on the 27th, 0.1 mm on 1st of November, and 0.2 mm on 2nd of November. The third sowing was performed on of November 9th; however, the precipitation of 0.5 mm occurred six days after the sowing on November 15th. Furthermore, on November 17th, the trial experienced 4.4 mm rainfall. The experiment underwent a warm winter with high precipitations in February (74.7 mm). Precipitation totaled 123 mm in May, and 111 mm in June.

Year 2017

In 2016/2017, the first sowing was on October 11th, and the first precipitation (0.1 mm) after sowing was on October 13th. The second sowing was on November 2nd, with 0.3 mm precipitation on the same day and 0.7 mm rain on November 4th. Compared to 2016, the year 2017 was arid. It is started with the coldest winter period from November until January, and the winter ended with a very warm temperature (4.9 and 9.1°C in February and March, respectively). From December until April, the value of precipitations was very low; it started with 9.2 mm rainfall in December and ended with 12.3 mm in April. However, in June, the precipitation was relatively high (113 mm).

Year 2018

In 2018, the experiment was established with only one sowing time on October 18th with low precipitation (0.1 mm) on the same day. On October 20th, precipitation was also low (0.3 mm), followed by 3.1 mm on October 21st. In November, the precipitation was increased to 98 mm. In January (6 °C) and February (-0.2 °C), the winter was relatively cold. The spring and summer were the hottest seasons for the trial, and the lowest precipitation occurred during May and July. In July, the precipitation amount was about 14 mm.

Year 2019

In 2018/2019, the first sowing was performed on October 9th; following a dry period with less precipitation (on 12th October 0.1 mm, on 24th October 0.3 mm and on 27th of October 1.3 mm, respectively). The second sowing was on October 31st. The day before, there had been roughly 2.4 mm of rain. The following rainfall was occurred on November 7th (0.7 mm). The precipitation in October was minimal (5 mm), but it was compensated by 91 mm of precipitation in December. The precipitation in February was once more minimal (6 mm). The year 2019 also was characterized by the hottest weather in June and low precipitation.

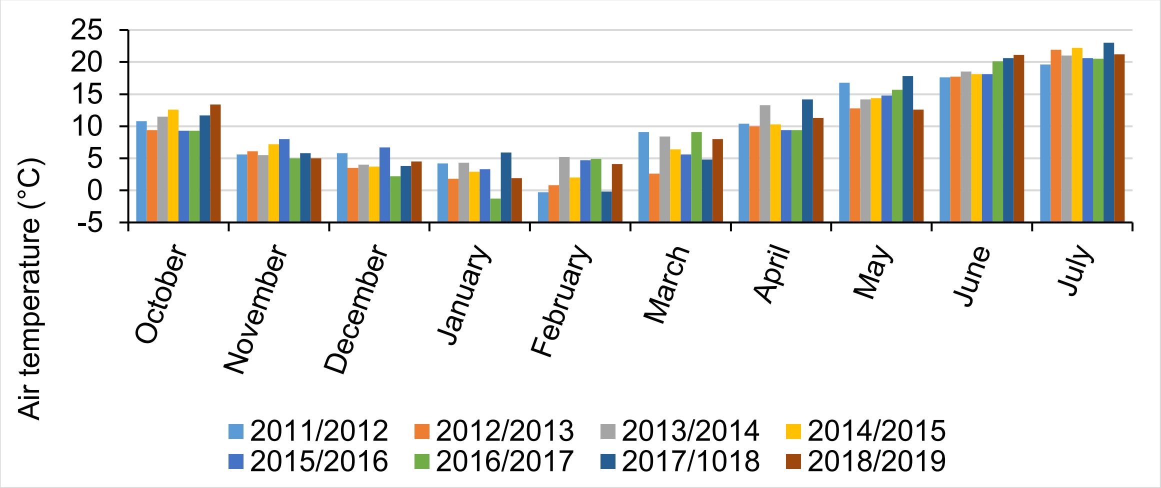

Figure 5: Air temperature (means per month in °C) during the growth cycle of winter wheat, experimental station Gross Gerau 2011- 2019.

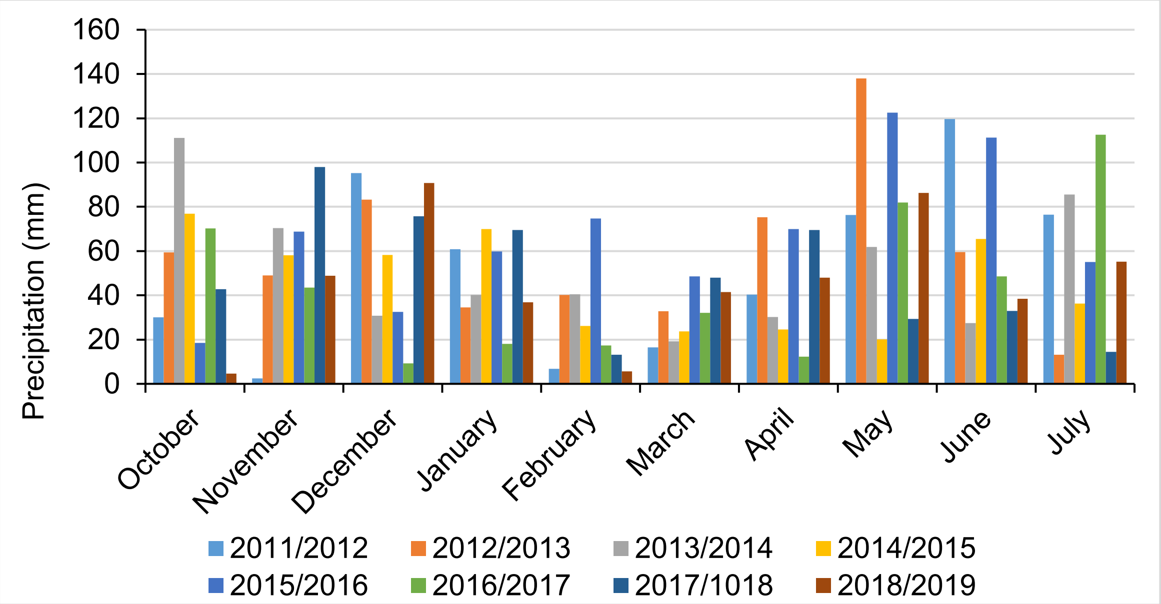

Figure 4: Precipitation sums per month (mm) during the growth cycle of winter wheat, experimental station Gross Gerau 2011-2019.

3.3.3 Rauischholzhausen

Year 2016

In 2015/2016, the first sowing was performed on October 11th, and the first precipitation was recorded after the sowing on 13th and 14th of October (0.3 and 1.3 mm, respectively). The second sowing was performed on November 7th, and the first precipitation (9.1 mm) was occurred on November 13th. In December, the weather was warm, with an average air temperature of 7 °C. There was enough precipitation (89 mm) in June, was followed by dry weather conditions in July and August.

Year 2017

In 2016/2017, the first sowing was on October 12th, followed by 0.3 mm precipitation at the next day and ongoing precipitations in the following days. The second sowing was on October 27th; in the same day, the precipitation was about 0.3 mm, and the next rainfall (1.3 mm) was occurred on October 29th. The winter was cold and dry with an average air temperature of -1.9 °C in January and 7.2 mm of precipitation in December, was followed by a warm and dry spring with 18.3 mm of precipitation in April (Figure 6).

Year 2018

In the growing season of 2017/2018, the experiment was established only with one sowing on 19th of October. The first precipitation (1.3 mm) after sowing was recorded on October 27th. In winter, there was adequate rainfall, 78 mm in December and 103 mm in January. The trial was experienced cold weather in February with an average temperature of -1.0 °C and 9 mm precipitation, was followed by a warm spring with the average temperature (April 13.2 °C, May 16.7 °C and June 18.8 °C).

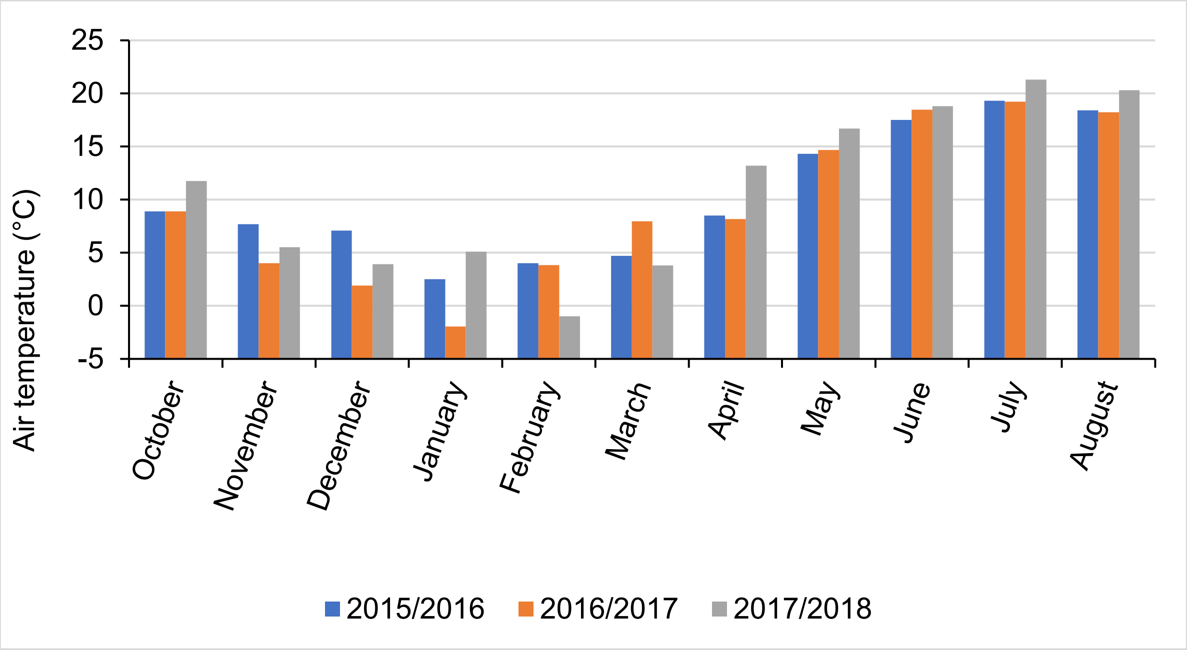

Figure 6: Air temperature (means per month in °C) during the grow cycle of winter wheat, experimental station Rauischholzhausen 2015- 2018.

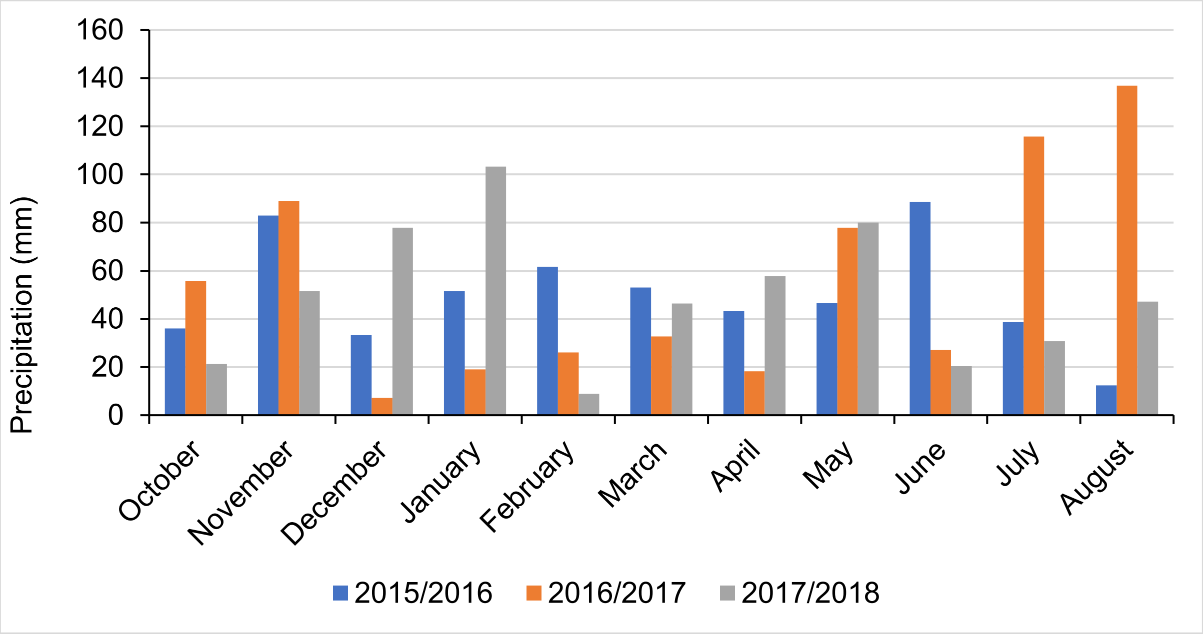

Figure 7: Precipitation sum per month (mm) during the growth cycle of winter wheat, experimental station Rauischholzahusen 2015-2018.

3.4 Statistical analysis

The variance analysis (ANOVA) was executed by Satterthwaite's Method. It is defined for each year and location if the data were normally distributed, and the variances were homogeneous. The significance level was p ≤0.05. A compact letter display (cld) with the Tukey additivity test was used for the pairwise comparisons. The replications in ANOVA were used as a random and as a fixed effect. The double use leads to no differences in the statistical results of the other parameters compared to an ANOVA where the replications were just used as a random effect but shows further information. If the replications differed significantly from each other, the blocks showed different yield potential and the scattering of yield increase for each variety.

Emmean: Estimated marginal means. The basic mean is extracted from statistical model and represents the average of response variable. A marginal mean is the mean response for each category of a factor adjusted for any other variables in the model. The marginal mean is used if interactions are in the model.

SE: Standard error. The model uses all the cases to compute the single estimate of the standard error. The model is that each group has its own mean but the variation about that mean is the same for all groups. This assumption that the variation about the group mean is the same for all groups is called homogeneity of variance.

Df: Numerator degree of freedom. The degree of freedom refers to the maximum number of logically independent values. The degree of freedom is calculated as followed:

Df= ((n (cultivars) -1) * (n (sowing times)-1)) -1

The number of cultivars minus one is multiplicated with the number of sowing times minus one in a normal ANOVA. In the Tukey additivities test it is minus one in the end.

Lower CI/ Upper CI (Confidence Interval): the confidence interval would declare if in statistical analysis the estimation of values would repeatable or not.

An ANOVA table is provided for each year and location, which includes the cultivars, sowing times, replications, and the interaction effect. Another ANOVA table was prepared to demonstrate the interactions among hybrid and line cultivars by different sowing times.

Levene's test (Levene 1960) is used to see if the variances of the line and hybrid cultivars were equal. A Welch t-test is used when there was a significant difference in variances; otherwise, a student t-test is utilized.

The statistical analyses were carried out with R software (version 4.0.4) was used packages of lmerTest (3.1-3), lme4 (1.1-26), emmeans (1.5.4), ggplot2 (3.3.3), ggsignif (0.6.1), ggrepel (0.9.1), ggsci (2.9) and GGally (2.1.1).

Weather Statistic

To recognize the effect of climate conditions on grain yield of hybrid and line cultivars the correlation matrix, ggpairs by the GGally (2.1.1) package from R (version 4.0.4) was used. The command gives three pieces of information of each correlation, first a histogram that gives the possibility to proof normal distribution, the correlation coefficient (r) and a correlation graphic, where outliers can be identified. Further on the matrix gives the option to compare different correlations with each other in just one graph. This analysis was chosen to show the influence of NODs, precipitation and global radiation on the grain yield of hybrids, line cultivars and the yield difference between both groups of cultivar types. The yield difference was calculated by the deviation of hybrid yield minus line yield. For that, the mean yield of all lines and the mean yield of all hybrids of each sowing time in each year were taken.

Number of Days (NOD)

In the first part, number of days (NOD) of a cropping season was counted, first from sowing until harvest, second from sowing until end of December and third from 01 January until harvest, to differentiate the influence of days in a cropping season.

In a second part the influence of NODs with specific air temperatures was analyzed. For this reason, the NODs from sowing till harvest was counted under 0°C, over 5°C, under 5°C, over 10°C, over 15°C and over 20°C. The growing season of wheat begins with over 5°C because of that, it was also differentiated between the NODs over 5°C from 01 January till harvest and the NODs over 5°C from sowing till end of December.

The data were collected from the weather stations, which are established in each field station (GI, GG and RH), in addition, the missing data were taken from the data collection of LLH (Landesbetrieb Landwirtschaft Hessen).

Precipitation (PPT)

The impact of the PPT from sowing to end of August, the PPT from 01 March to 31 August, and the PPT from 01 May to 31 August was investigated. The data were collected from the weather stations, which are established in each field station (GI, GG and RH), in addition, the missing data taken from the data collection of LLH.

Global radiation (GR)

The global radiation (kWh/m²) data were taken from the data collection of LLH for each field site. The total global radiation of a cropping season was compared with the influence of the global radiation from 01 March until harvest. Also, the influence of the global radiation on the yield difference between the first and second sowing time of each hybrid and line cultivars was tested to show if the amount of global radiation caused by an earlier/later sowing had an influence on the yield difference between the sowing times, and if hybrids and lines react differently to this condition.

Yield stability of hybrids and lines

For the yield stability just three years (2012-2014) and six cultivars (Hybery, Hybred, Hystar, Lear, Linus, and Meister) were used, because the cultivars changed often in the running time for the project. To calculate the dynamic stability the methods for measurements which are mentioned by Shukla's (1972a) stability variance and Wricke's (1962) ecovalence and (Becker and Léon, 1988) are used. For ease of calculations for the genotype and comprehensive of results, Wricke's ecovalence and the regression method by Eberhart and Russell are used to calculate the yield stability in this study.

Wricke's ecovalence (Wricke 1962) is based on the allocation of the genotype-environment-index (GEI) to each cultivar. The cultivar, which contributes the smallest value to the total GEI, is the most stable. For each cultivar i, the sum of the squares of the deviations of the cultivar over the different environments formed. Ecovalency of cultivar i = Wi. After calculation, the cultivars ranked according to their Wi values. The sum of the Wi values is equal to the mean square sum (SQ) of the GEI.

$$Wi = (x_{ij} - \overline{x}_{i.} - \overline{x}_{.j} + \overline{x}_{...})^2$$

Eberhart and Russell 1966 established a stability method based on the regression of the cultivar's values to the environmental mean values called environmental indices. The analysis gives two parameters. The first parameter is bi (the regression coefficient of variety i). Eberhart and Russel explained a stable genotype as a variety with high mean values and a bi of one. Actually, a bi value bigger than one shows an intensive variety that produces an above-average increase in productivity in more productive environments. A bi value lower than one indicates an extensive variety, which does not respond to more productive environmental conditions, but may perform better than an intensive variety in extreme locations. The second parameter is the sum of squares for variety i (s^2di) it describes the spread around the regression line. A stable cultivar should have a value of zero according to Eberhart and Russell. A high value could give a hint of a cultivar which is beneficial for a local use.

4 Results

4.1 Yield comparisons of the wheat cultivars in Giessen

4.1.1 Year 2012

In Giessen 2012, the data set for the analysis of variance (ANOVA) consisted of eight wheat cultivars (CV) in combination with three different sowing timings. CV Egoist was taken out from the evaluation because the large variances distorted the statistical results.

Two ANOVA evaluations were carried out on the data to test for possible variety x sowing time interactions: (1) Firstly, all eight varieties were included and their reaction to sowing time was tested (interaction varieties x sowing time). (2) Secondly, only the two cultivar types (CT) (line vs. hybrid varieties) were examined with regard to their reaction to sowing time (interaction cultivar type x sowing time).

According to the first ANOVA, the grain yields of wheat cultivars were significantly different ($p<0.001$), whereas no significant differences between sowing times were found ($p=0.349$) (Table 9). However, the effects of the cultivars were overlaid by the significant interaction of cultivar (CV) x sowing time (ST) ($p=0.019$) (Table 9).

Table 9: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Giessen 2012.

Source of Variation	SS	MS	DF	F value	*p*-value
Replications	15.8	15.76	1	0.7078	0.489
Cultivars (CV)	8345.5	1192.22	7	53.5434	< 0.001
Sowing time (ST)	47.6	23.82	2	1.0697	0.349
CV × ST	667.5	47.68	14	2.1412	0.019

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source

Three out of four hybrid cultivars (Hymack, Hybery and Hybred) had higher yields compared to the line cultivars. Among the hybrid cultivars, Hymack yielded the most in the first sowing time (95.4 dt/ha) (Figure 8). Delaying sowing, on the other hand, led to a reduction in grain yields for Hymack, but even then, they were still higher than those of most other comparison varieties. In contrast, the hybrid variety Hystar achieved only comparatively low yields, ranking in the lower third of the yield scale (Figure 8).

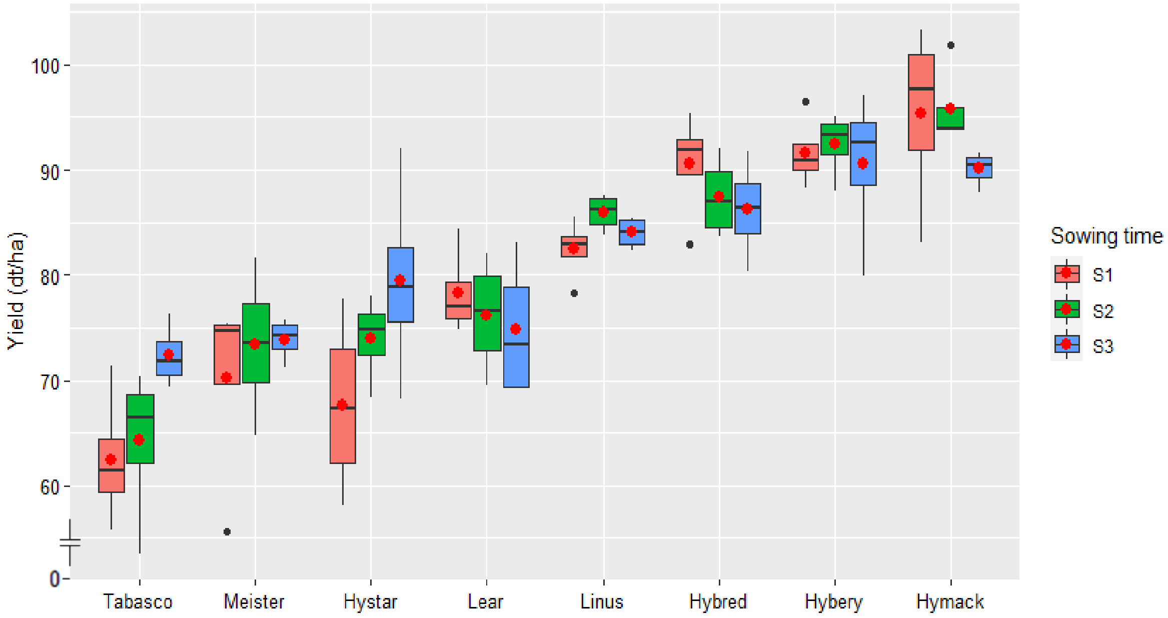

Figure 8: Grain yield comparison (dt/ha) of winter wheat cultivars depending on sowing times (*p*-value CV x ST =0.019), Giessen 2012. The lines show the scattering range, and the black point indicates the out-layer, S1 early, S2 medium, S3 late sowing time.

According to Table 10, hybrid wheat cultivars surpass line cultivars in terms of yield. The wheat cultivars with the highest and lowest grain yields were Hymack (95 dt/ha) and Tabasco (62 dt/ha) respectively.

In the second ANOVA performed on the data, no interaction was found between cultivar type (CT) and sowing time (ST) (*p*=0.824) (Table 11). This result confirms that within the cultivar type not all cultivars reacted the same (but differently) to ST. However, the hybrid varieties were on average significantly higher yielding than the line varieties (*p*<0.001) (Figure 9). In the mean of the sowing times, this yield superiority amounted to 13 dt/ha.

Table 10: Compact letter display of the cultivars corresponding to the sowing times, Giessen 2012. SE= standard error, DF= degree of freedom, lower CI= confidence interval, Group= the characters with the same letter are not significantly different from each.

Cultivars	Sowing time	Mean	SE	DF	Lower CI	Upper CI	Group
Tabasco (L)	S1	62.5	2.93	13	56.1	68.8	A
Tabasco (L)	S2	64.2	2.93	13	57.9	70.6	AB
Hystar (H)	S1	67.6	2.93	13	61.3	74.0	ABC
Meister (L)	S1	70.2	2.93	13	63.8	76.5	ABCD
Tabasco (L)	S3	72.3	2.93	13	66.0	78.7	ABCDE
Meister (L)	S2	73.4	2.93	13	67.1	79.7	ABCDEF
Meister (L)	S3	73.9	2.93	13	67.5	80.2	ABCDEFG
Hystar (H)	S2	74.0	2.93	13	67.7	80.3	ABCDEFG
Lear (L)	S3	74.8	2.93	13	68.5	81.1	ABCDEFGH
Lear (L)	S2	76.2	2.93	13	69.8	82.5	BCDEFGH
Lear (L)	S1	78.3	2.93	13	72.0	84.6	CDEFGHI
Hystar (H)	S3	79.5	2.93	13	73.1	85.8	CDEFGHIJ
Linus (L)	S1	82.5	2.93	13	76.1	88.8	DEFGHIJK
Linus (L)	S3	84.0	2.93	13	77.7	90.4	EFGHIJKL
Linus (L)	S2	85.9	2.93	13	79.6	92.3	FGHIJKL
Hybred (H)	S3	86.2	2.93	13	79.9	92.5	GHIJKL
Hybred (H)	S2	87.4	2.93	13	81.1	93.7	HIJKL
Hymack (H)	S3	90.1	2.93	13	83.8	96.4	IJKL
Hybred (H)	S1	90.5	2.93	13	84.2	96.9	IJKL
Hybery (H)	S3	90.5	2.93	13	84.2	96.9	IJKL
Hybery (H)	S1	91.6	2.93	13	85.3	98.0	JKL
Hybery (H)	S2	92.5	2.93	13	86.1	98.8	KL
Hymack (H)	S1	95.4	2.93	13	89.1	101.7	L
Hymack (H)	S2	95.8	2.93	13	89.5	102.2	L

Table 11: Two-way ANOVA of grain yields depending on cultivars (line vs. hybrid) and sowing times, Giessen, 2012.

Source of variation	SS	MS	DF	F value	*p*-value
Replications	57.8	57.8	1	0.7077	0.489
Cultivar type (hybrids/lines) (CT)	3412.9	3412.9	1	41.7929	< 0.001
Sowing time (ST)	47.6	23.8	2	0.2917	0.748
Hybrids / Lines × ST	31.8	15.9	2	0.1947	0.824

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source

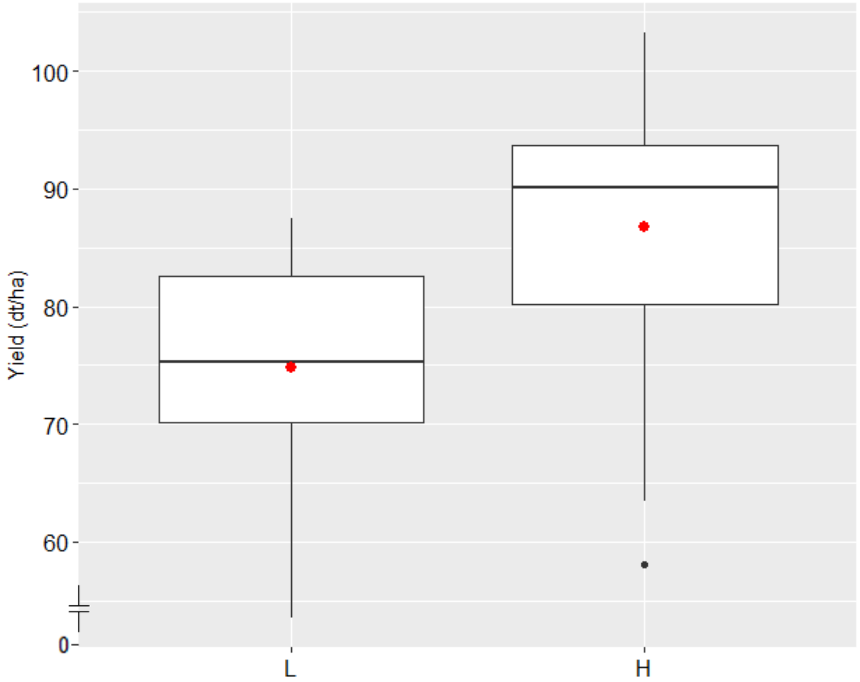

Figure 9: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 4 lines), (*p*-value$_{(CV)}$ <0.001), Giessen 2012. The lines show the scattering, and the black point indicates the out-layer.

4.1.2 Year 2013

The data set used for ANOVA in 2013 included nine different wheat cultivars and three varying sowing times. As a result of the statistical evaluation, an interaction between the two test factors CV and ST was found, indicating a differentiated varietal reaction to the sowing time delay. (p<0.001). In addition to the existing interaction, there were also statistically confirmed yield differences between the cultivars (p<0.001) and between the sowing times (main effects in each case) (p=0.020) (Table 12).

Table 12: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Giessen 2013.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	16.6	16.06	1	1.8710	0.305
Cultivars (CV)	1745.35	218.16	8	25.4154	< 0.001
Sowing time (ST)	115.90	57.95	2	6.7509	0.020
CV × ST	650.72	40.67	16	4.7379	< 0.001

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source

The existing CV x ST interaction was triggered in 2013 by a strongly varying reaction of the varieties to the sowing time delay. Thus, the grain yields of the varieties Tabasco, Egoist and Lear dropped drastically in the second and especially in the third sowing time (Figure 10). In contrast, the varieties Meister, Hystar and Hybery showed an increase in yields as a result of the sowing time delay. The other varieties were relatively neutral, their grain yields changing only slightly as a result of the change in sowing time (Figure 10).

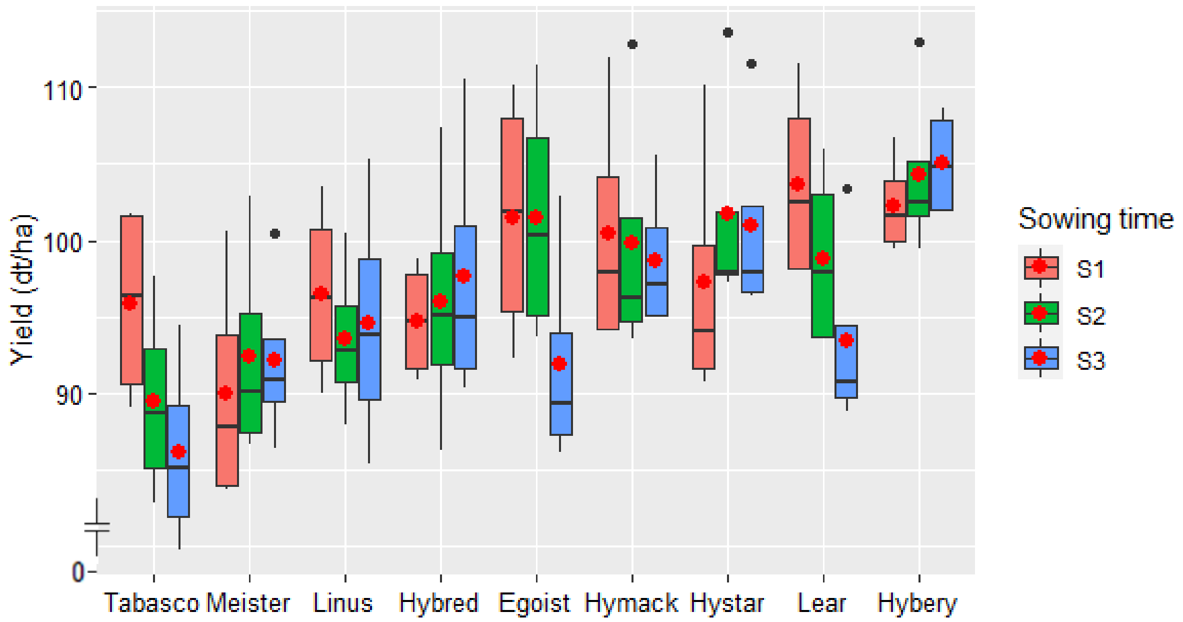

Figure 10: Yield comparison (dt/ha) of the cultivars under the influence of the sowing times, *p*-value$_{(CVxST)}$ <0.001, Giessen 2013. The lines show the scattering range, the black point the out-layer, the red points the mean, S1 early, S2 medium, S3 late sowing time.

The maximum yield was associated with the hybrid Hybery at the third sowing time, while the lowest yield was associated with the line cultivar Tabasco at the third sowing time (Table 13).

In the result of the second ANOVA, it was found that there was also a significant interaction between the test factors CT x ST (*p*<0.003) (Table 14). This means that not only the individual cultivars reacted specifically to the sowing time, but the entire variety group of the line varieties behaved differently than that of the hybrids (Figure 11).

Table 13: ANOVA of different cultivars and sowing times, Giessen 2013. SE= standard error, DF= degree of freedom, lower CI= confidence interval, Group= the characters with the same letter are not significantly different from each other.

Cultivars	Sowing time	Mean	SE	DF	Lower CI	Upper CI	Group
Tabasco (L)	S3	86.1	3.19	3.15	76.2	96.0	A
Tabasco (L)	S2	89.5	3.19	3.15	79.6	99.3	AB
Meister (L)	S1	90.0	3.19	3.15	80.1	99.8	ABC
Egoist (L)	S3	91.9	3.19	3.15	82.0	101.8	ABCD
Meister (L)	S3	92.2	3.19	3.15	82.3	102.0	ABCD
Meister (L)	S2	92.5	3.19	3.15	82.6	102.3	ABCD
Lear (L)	S3	93.4	3.19	3.15	83.5	103.3	ABCDE
Linus (L)	S2	93.5	3.19	3.15	83.6	103.4	ABCDEF
Linus (L)	S3	94.6	3.19	3.15	84.7	104.5	BCDEFG
Hybred (H)	S1	94.8	3.19	3.15	84.9	104.6	BCDEFG
Tabasco (L)	S1	95.9	3.19	3.15	86.0	105.8	BCDEFGH
Hybred (H)	S2	96.0	3.19	3.15	86.1	105.8	BCDEFGH
Linus (L)	S1	96.5	3.19	3.15	86.6	106.4	BCDEFGHI
Hystar (H)	S1	97.3	3.19	3.15	87.4	107.2	BCDEFGHIJ
Hybred (H)	S3	97.7	3.19	3.15	87.8	107.6	CDEFGHIJ
Hymack (H)	S3	98.7	3.19	3.15	88.8	108.6	DEFGHIJ
Lear (L)	S2	98.8	3.19	3.15	88.9	108.7	DEFGHIJ
Hymack (H)	S2	99.8	3.19	3.15	89.9	109.7	DEFGHIJ
Hymack (H)	S1	100.5	3.19	3.15	90.6	110.4	EFGHIJ
Hystar (H)	S3	100.9	3.19	3.15	91.0	110.8	EFGHIJ
Egoist (L)	S2	101.4	3.19	3.15	91.5	111.3	FGHIJ
Egoist (L)	S1	101.5	3.19	3.15	91.6	111.4	GHIJ
Hystar (H)	S2	101.7	3.19	3.15	91.8	111.6	GHIJ
Hybery (H)	S1	102.3	3.19	3.15	92.4	112.2	GHIJ
Lear (L)	S1	103.7	3.19	3.15	93.8	113.5	HIJ
Hybery (H)	S2	104.3	3.19	3.15	94.4	114.2	IJ
Hybery (H)	S3	105.0	3.19	3.15	95.2	114.9	J

Table 14: Two-way ANOVA of grain yields depending on cultivars (line vs. hybrid) and sowing times, Giessen, 2013.

Source of variation	SS	MS	DF	F value	*p*-value
Replications	39.51	39.51	1	2	0.305
Cultivar type (hybrids/lines) (CT)	708.3	708.3	1	34	<0.001
Sowing time (ST)	81.17	40.58	2	2	0.152
Hybrids / Lines × ST	266.66	133.33	2	6.3135	0.003

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

In general, hybrid wheat cultivars yielded significantly more than lines. This difference was greater in the second and third sowing. In contrast, both hybrid and line cultivars produced comparable grain yields (98.7 and 97.5 dt/ha, respectively) in the first sowing time (Figure 11). However, with the delay in sowing, significant differences in grain yields emerged. In the line varieties, the delay in sowing in S2 and in S3 caused a significant reduction in yields, indicating a deterioration in growing conditions. In contrast, the yields of the hybrid varieties remained at the same level or increased slightly even with late sowing, suggesting a certain tolerance of the late sowing conditions (Figure 11).

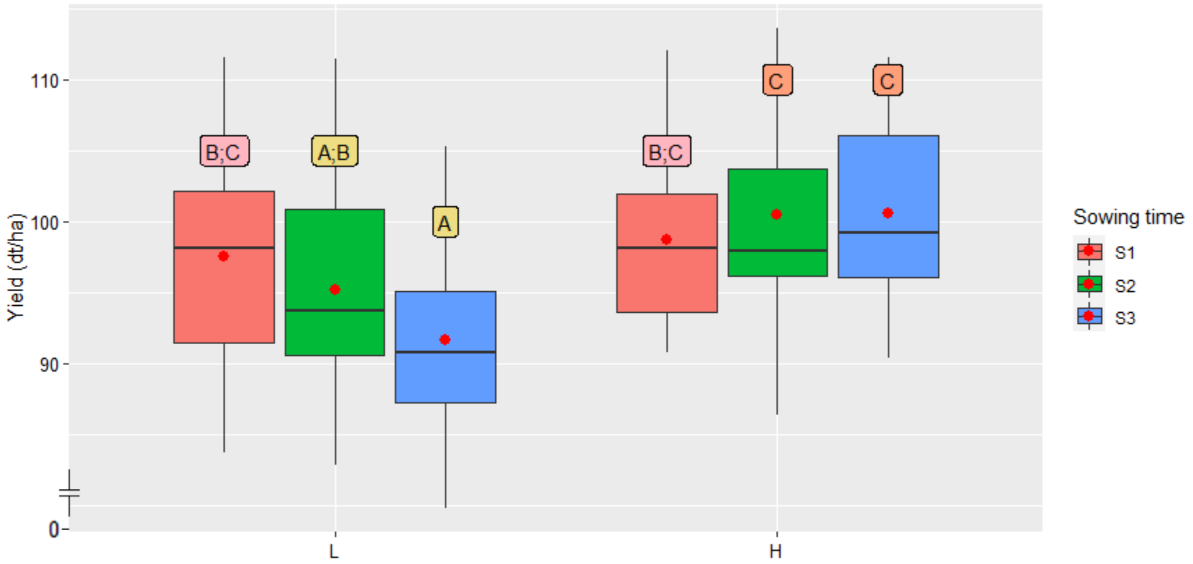

Figure 11: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines) under the influence of the sowing times, *p*-value$_{(CV\times ST)}$ =0.003, Giessen 2013. The lines show the scattering, the black point the out-layer, the red points the mean, S1 early, S2 medium, S3 late sowing time.

4.1.3 Year 2014

The data set used for ANOVA in 2014 included nine different wheat cultivars and three varying sowing times. As a result of the statistical evaluation, an interaction between the two test factors CV x ST was found, indicating a differentiated varietal reaction to the sowing time delay. (*p*<0.001) (Table 15). In addition to the existing interaction, there were also statistically confirmed yield differences between the cultivars (*p*<0.001) and between the sowing times (main effects in each case) (*p*<0.001) (Table 15).

Table 15: Two-way ANOVA of the yields depending on different cultivars and sowing times, Giessen 2014.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	2.53	2.53	1	0.2137	0.689
Cultivars (CV)	1465.55	183.19	8	15.478	< 0.001
Sowing time (ST)	1203.12	601.56	2	50.8256	< 0.001
CV × ST	851.29	53.21	16	4.4953	< 0.001

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

The existing CV x ST interaction was triggered in 2014 by a strongly varying reaction of the varieties to the sowing time delay. Thus, the grain yields of all cultivars except Hybery dropped drastically in the second and third sowing time (Figure 12). However, the intensity of reaction was different between cultivars. In contrast, the variety Hybery showed small increase in yields as a result of the second sowing time delay (Figure 12).

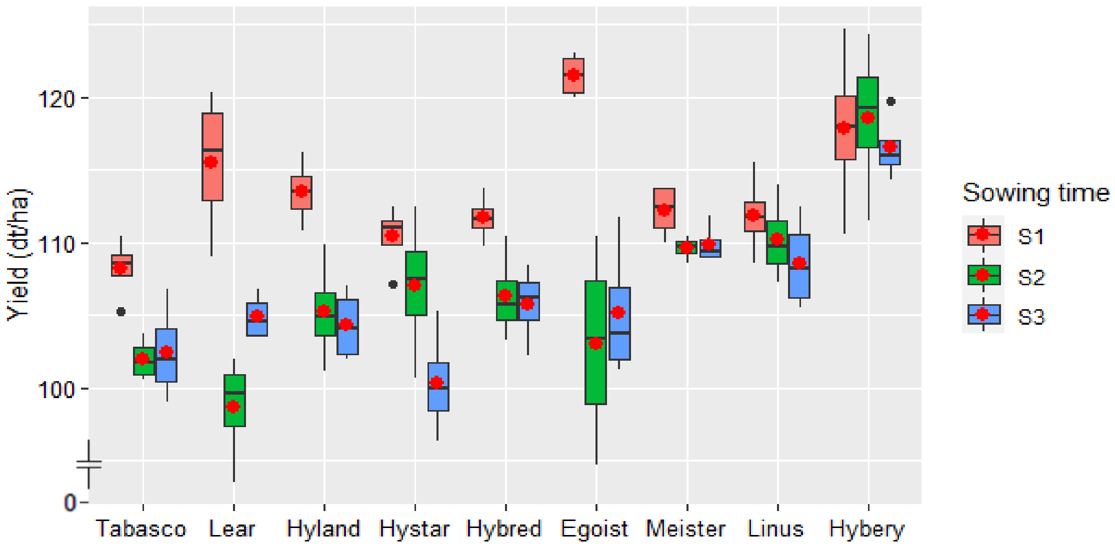

Figure 12: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines) under the influence of the sowing times, *p*-value$_{(CV×ST)}$ <0.001, Giessen, 2014. The lines show the scattering, the black point the out-layer, the red points the mean, S1 early, S2 medium, S3 late sowing time.

All examined cultivars except Hybery, yielded more at the first sowing time than at the second and third sowing time (Figure 12). The maximum yield was achieved by Egoist at the first sowing time (121.5 dt/ha), however, Hybery produced the highest yield in mean (117.8 dt/ha) over all sowing times comparable to Egoist which had high yield variability across all three sowing times (Table 16).

According to the second ANOVA, there were no significant interactions between cultivar type (hybrids/lines) but there were significant differences between the test factors sowing time (*p*<0.001) (Table 17). This result confirms that within the cultivar type not all cultivars reacted in the same to sowing time.

Table 16: Compact letter display of the cultivars under the influence of the sowing times, Giessen 2014. SE= standard error, DF= degree of freedom, lower CI= confidence interval, group= the characters with the same letter are not significantly different from other.

Cultivars	Sowing time	Mean	SE	DF	Lower CI	Upper CI	Group
Lear (L)	S2	98.6	1.73	78.8	95.2	102	A
Hystar (H)	S3	100.3	1.73	78.8	96.9	104	AB
Tabasco (L)	S2	101.9	1.73	78.8	98.5	105	ABC
Tabasco (L)	S3	102.5	1.73	78.8	99.0	106	ABCD
Egoist (L)	S2	103.0	1.73	78.8	99.5	106	ABCDE
Hyland (H)	S3	104.3	1.73	78.8	100.8	108	ABCDEF
Lear (L)	S3	104.9	1.73	78.8	101.4	108	ABCDEF
Egoist (L)	S3	105.1	1.73	78.8	101.7	109	ABCDEF
Hyland (H)	S2	105.2	1.73	78.8	101.8	109	ABCDEF
Hybred (H)	S3	105.8	1.73	78.8	102.3	109	ABCDEF
Hybred (H)	S2	106.3	1.73	78.8	102.9	110	ABCDEFG
Hystar (H)	S2	107.0	1.73	78.8	103.6	110	ABCDEFG
Tabasco (L)	S1	108.2	1.73	78.8	104.8	112	BCDEFGH
Linus (L)	S3	108.6	1.73	78.8	105.1	112	BCDEFGHI
Meister (L)	S2	109.6	1.73	78.8	106.2	113	BCDEFGHIJ
Meister (L)	S3	109.9	1.73	78.8	106.4	113	CDEFGHIJ
Linus (L)	S2	110.2	1.73	78.8	106.8	114	CDEFGHIJ
Hystar (H)	S1	110.4	1.73	78.8	107.0	114	CDEFGHIJ
Hybred (H)	S1	111.7	1.73	78.8	108.3	115	DEFGHIJ
Linus (L)	S1	111.9	1.73	78.8	108.5	115	EFGHIJ
Meister (L)	S1	112.2	1.73	78.8	108.8	116	EFGHIJ
Hyland (H)	S1	113.5	1.73	78.8	110.1	117	FGHIJK
Lear (L)	S1	115.5	1.73	78.8	112.0	119	GHIJK
Hybery (H)	S3	116.5	1.73	78.8	113.1	120	HIJK
Hybery (H)	S1	117.8	1.73	78.8	114.4	121	IJK
Hybery (H)	S2	118.6	1.73	78.8	115.2	122	JK
Egoist (L)	S1	121.5	1.73	78.8	118.1	125	K

Table 17: Two-way ANOVA of grain yields depending on cultivars (line vs. hybrid) and sowing times, Giessen, 2014.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	3.06	3.06	1	0.1005	0.751
Cultivar type (hybrids/lines) (CT)	64.03	64.03	1	2.1035	0.150
Sowing time (ST)	1134.54	567.27	2	18.6353	< 0.001
Hybrids / Lines × ST	130.12	65.06	2	2.1372	0.123

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

The yield performance of the CT hybrid (113.9 dt/ha) and line (113.4 dt/ha) were equal at first sowing time. Furthermore, for both hybrid and line cultivars, the first sowing time yielded more than the second and third sowing times. However, the negative reaction by lines to late sowing time was significantly greater than the hybrid cultivars (Figure 13).

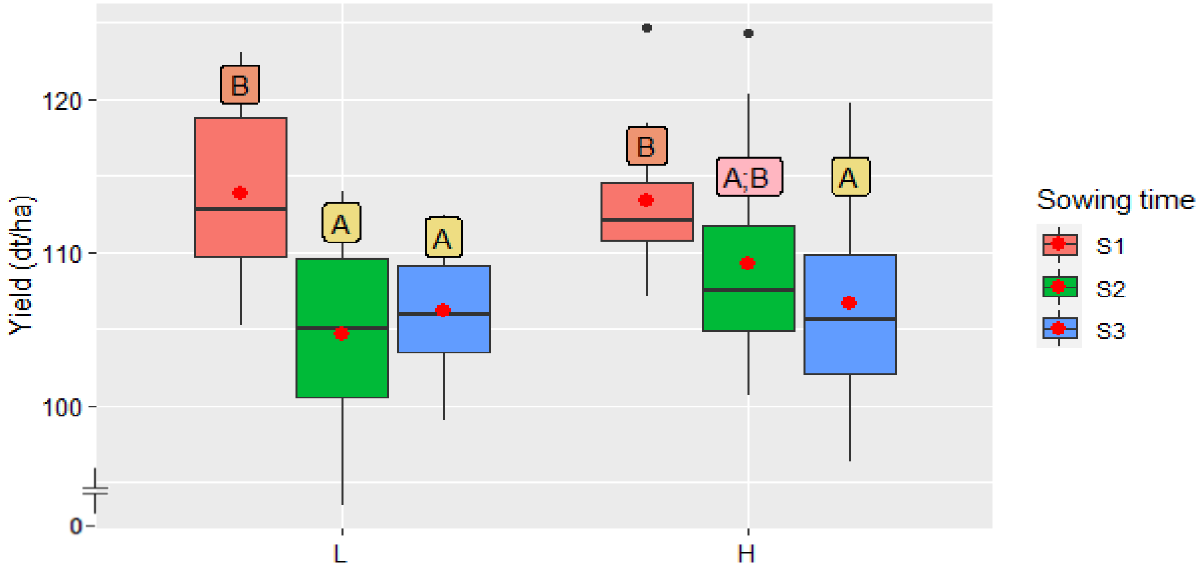

Figure 13: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines) under the influence of the sowing times, *p*-value$_{(ST)}$ <0.001, Giessen 2014. The lines show the scattering range, the black point the out-layer, the red points the mean, S1 early, S2 medium, S3 late sowing time.

4.1.4 Year 2015

The data set used for ANOVA in 2015 included nine different wheat cultivars and three varying sowing times. As a result of the statistical evaluation, there were statistically confirmed yield differences between the cultivars (*p*<0.001) and between the sowing times (main effects in each case) (*p*<0.001). There were no significant differences in interactions between CV x ST (*p*=0.069) (Table 18).

Table 18: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Giessen, 2015.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	269.66	269.66	1	9.0488	0.003
Cultivars (CV)	2507.95	313.49	8	10.5196	< 0.001
Sowing time (ST)	1038	519	2	17.4156	< 0.001
CV × ST	797.82	49.86	16	1.6732	0.069

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

Hymack and Hyland had the highest yield compared with other cultivars. The lowest grain yield recorded by Meister (Figure 14).

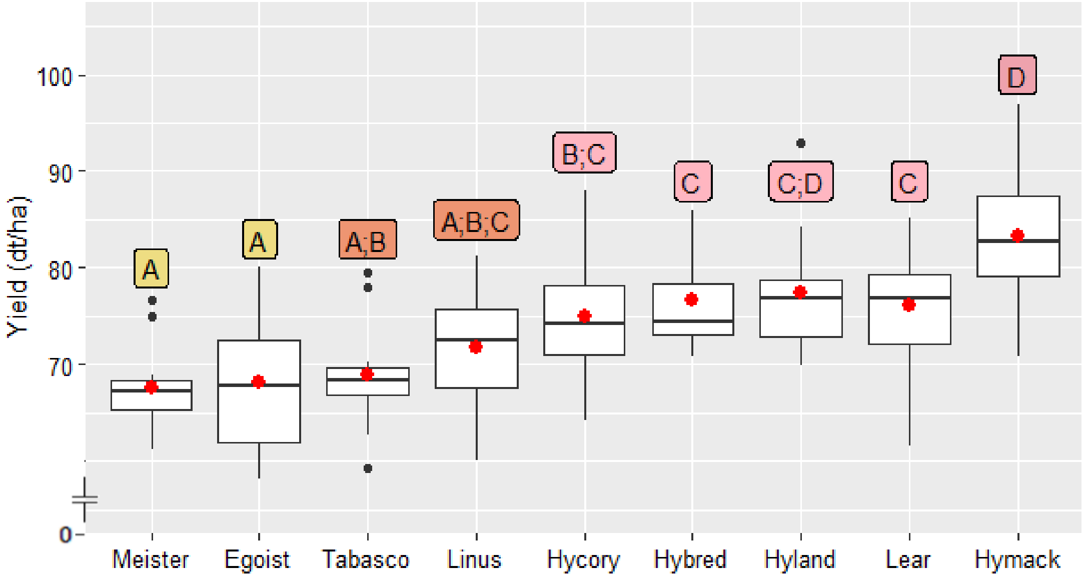

Figure 14: Yield comparison (dt/ha) of wheat cultivars (*p*<0.001), Giessen 2015. The yield of each variety is composed of three sowing times and four repetitions. The lines show the scattering range, the black point the out-layer, the letters above the cld the red points the mean.

In the second ANOVA performed on the data, no significant interaction was found between cultivar type (CT) x sowing time (ST) (*p*=0.08) (Table 19). However, yield differences between hybrid and line cultivars were highly significant (*p*<0.001), also there were significant differences between the sowing times (*p*<0.001). Both line and hybrid cultivars showed the lowest yield at the second sowing time (Figure 15). Hybrids had the highest yield in the latest ST, while lines showed no differences between the first and last ST. In general, hybrid varieties were on average significantly higher yielding than the line varieties (*p*<0.001) (Figure 15). In the mean of the sowing times, this yield superiority amounted to 8 dt/ha.

Table 19: Two-way ANOVA of grain yields depending on cultivars (line vs. hybrid) and sowing times, Giessen, 2015.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	111.02	111.02	1	3.1933	0.215
Cultivar type (hybrids/lines) (CT)	1518	1518	1	43.661	< 0.001
Sowing time (ST)	1097.44	548.72	2	15.7823	< 0.001
Hybrids / Lines × ST	174.29	87.15	2	2.5065	0.087

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

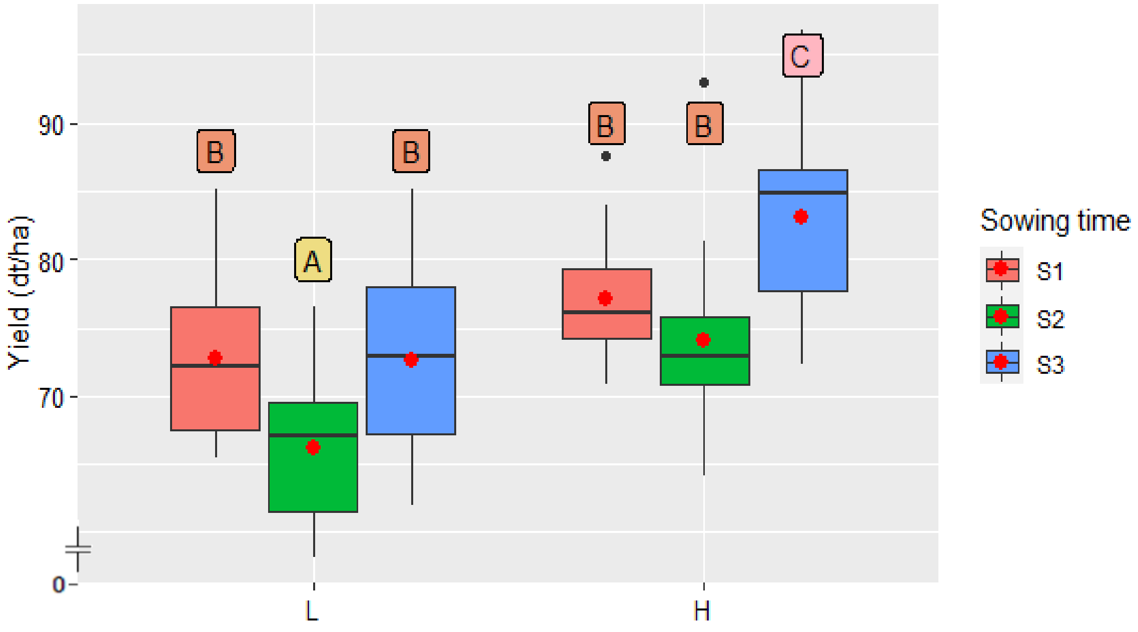

Figure 15: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines), depending on sowing times, *p*-value$_{(CV)}$ <0.001, Giessen 2015. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 medium, S3 late sowing time.

4.1.5 Year 2016

The data set used for ANOVA in 2016 included ten different wheat cultivars and three varying sowing times. According to the first ANOVA, the grain yields of wheat cultivars were significantly different (*p*<0.001), whereas no significant differences between sowing times were found (*p*=0.126). Interaction of cultivar (CV) x sowing time (ST) were not significant (*p*=0.773) (Table 20).

Table 20: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Giessen, 2016.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	2.9	2.86	1	0.0918	0.79
Cultivars (CV)	3347.9	371.99	9	11.9293	< 0.001
Sowing time (ST)	132	66.02	2	2.1172	0.126
CV × ST	408.6	22.7	18	0.728	0.773

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

Three out of four hybrid cultivars (Hystar, Hylux and Hyland) provided higher yields compared to the line cultivars (Figure 16). Grain yield of all line cultivars do not differ significantly from each other except Ambello which recorded lowest grain yield (86.2 dt/ha) (Figure 16).

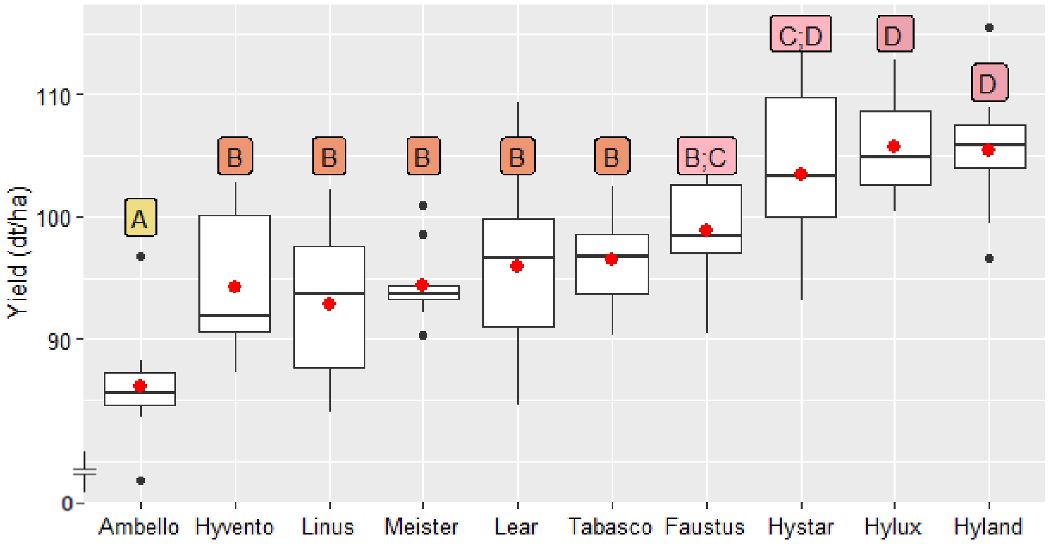

Figure 16: Yield comparison (dt/ha) of the cultivars, Giessen 2016. The lines show the scattering range, the black point the out-layer, the letters above the cld and the red points the mean.

In the second ANOVA performed on the data, no interaction was found between cultivar type (CT) *x* sowing time (ST) (*p*=0.53) (Table 21). However, yield differences between hybrid and line cultivars were highly significant (*p*<0.001). There were no significant differences in sowing time (*p*=0.305) as well (Table 21).

Table 21: Two-way ANOVA of grain yields depending on cultivars (line vs. hybrid) and sowing times, Giessen, 2016.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	5.42	5.42	1	0.1311	0.752
Cultivar type (hybrids/lines) (CT)	1893.57	1893.57	1	45.806	< 0.001
Sowing time (ST)	99.33	49.67	2	1.2014	0.305
Hybrids / Lines × ST	52.52	26.26	2	0.6352	0.532

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

The hybrid varieties were on average significantly higher yielding than the line varieties (*p*<0.001) (Figure 17). In the mean of the sowing times, this yield superiority amounted to 8 dt/ha.

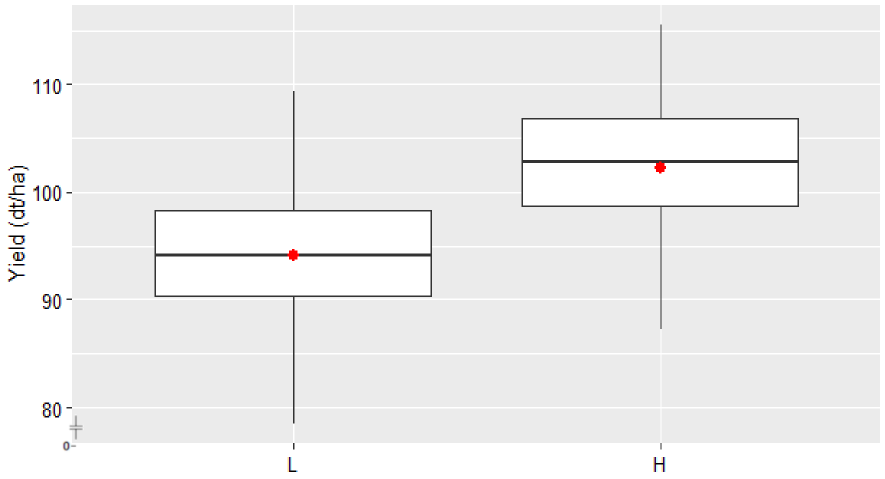

Figure 17: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 6 lines), depending on sowing times, p-value$_{(CT)}$ < 0.001, Giessen 2016. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 medium, S3 late sowing time.

4.1.6 Year 2017

The data set used for ANOVA in 2017 included ten different wheat cultivars and two varying sowing times. As a result of the statistical evaluation, there were statistically confirmed yield differences between the cultivars ($p<0.001$) and between the sowing times (main effects in each case) ($p<0.001$). There were no significant differences in interactions interaction of cultivar (CV) x sowing time (ST) ($p=0.061$) (Table 22).

Table 22: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Giessen, 2017.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	0	0.01	1	0.0007	0.981
Cultivars (CV)	3297.2	366.35	9	32.7459	< 0.001
Sowing time (ST)	1884.7	1884.71	1	168.463	< 0.001
CV × ST	197.2	21.92	9	1.9589	0.061

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

The best yield performance between cultivars was recorded by two hybrids (Hybery with 88.1 dt/ha and Hyvento with 85.4 dt/ha), however, the hybrid CV Hylux, with a mean yield of 64.5 dt/ha, recorded the significantly lowest yield compared to all other cultivars. The yield performance of the line cultivars Linus, Bonanza, and Meister showed similar results as two (Hyvento and Hyland) of four hybrid cultivars with 80.5–82.0 dt/ha (Figure 18).

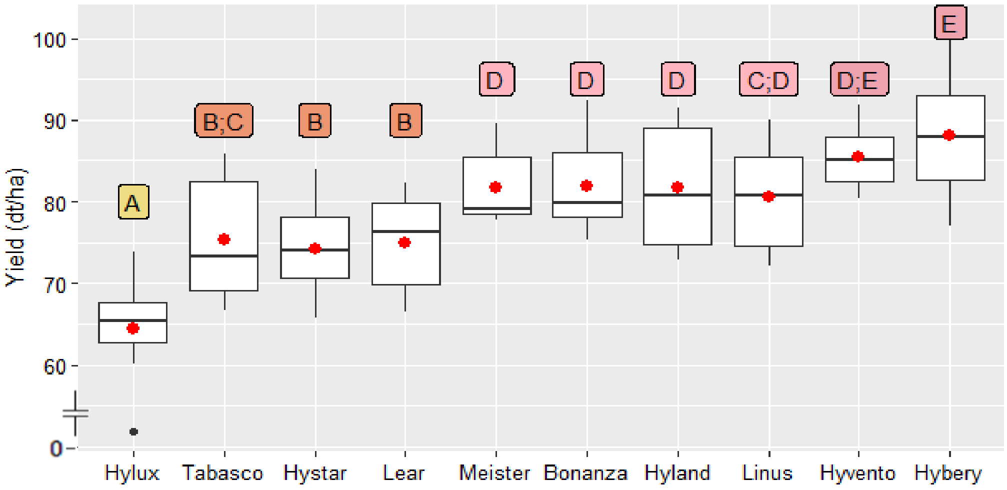

Figure 18: Yield comparison (dt/ha) of the cultivars (*p*<0.001), Giessen 2017. The lines show the scattering range, the black point the out-layer, the letters above the cld and the red points the mean.

According to the second ANOVA, there were no significant interactions between cultivar type (hybrids/lines) (*p*=0.959), implicated by the high scattering in the hybrid CV. However, there were significant differences between the sowing times (*p*<0.001) (Table 23).

Table 23: Two-way ANOVA of grain yields depending on cultivars (line vs. hybrid) and sowing times, Giessen, 2017.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	0.04	0.04	1	0.0007	0.981
Cultivar type (hybrids/lines) (CT)	0.15	0.15	1	0.0027	0.959
Sowing time (ST)	1884.71	1884.71	1	33.3072	< 0.001
Hybrids / Lines × ST	1.18	1.18	1	0.0208	0.886

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

The yield difference between the first and second sowing time was significant and cultivars recorded significantly higher grain yield in first sowing time (84 dt/ha) than in the second sowing time (74.0 dt/ha). In the mean of the sowing times, this yield superiority amounted to 10 dt/ha (Figure 19).

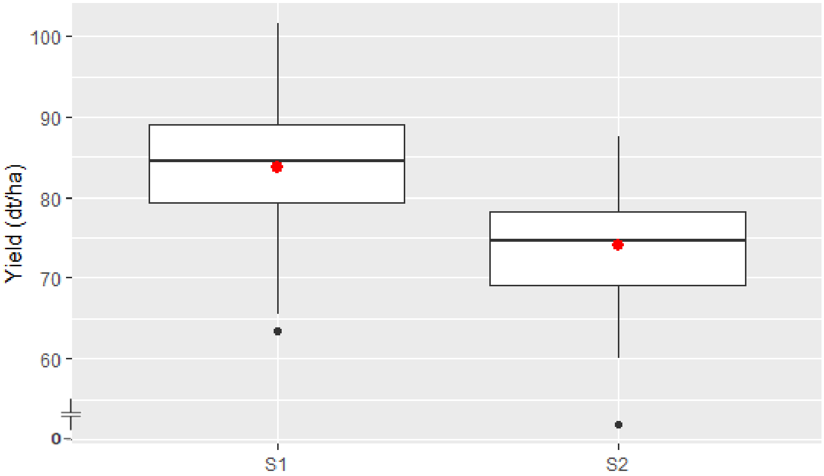

Figure 19: Yield comparison (dt/ha) of wheat cultivars (H: 5 hybrids, L: 5 lines), depending on sowing times, *p*-value$_{(CV)}$ <0.001, Giessen 2017. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 medium, S3 late sowing time.

4.1.7 Year 2018

The data set used for ANOVA in 2018 included eight different wheat cultivars and one sowing time. As a result of the statistical evaluation, there were statistically confirmed yield differences between the cultivars (*p*<0.001) (Table 24).

Table 24: One-way ANOVA of the grain yields depending on cultivars and sowing times, Giessen, 2018.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	0.02	0.022	1	0.0028	0.962
Cultivars (CV)	1053.71	150.53	7	19.5391	< 0.001

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

The highest yielding cultivar was the line CV Lear (118.5 dt/ha), which differed significantly from all other CV except Hybery (112.9 dt/ha). Two of three hybrids (Hybery and Hyvento) were high yielding while the hybrid cultivar Hylux recorded the lowest yield (99.5 dt/ha) (Figure 20).

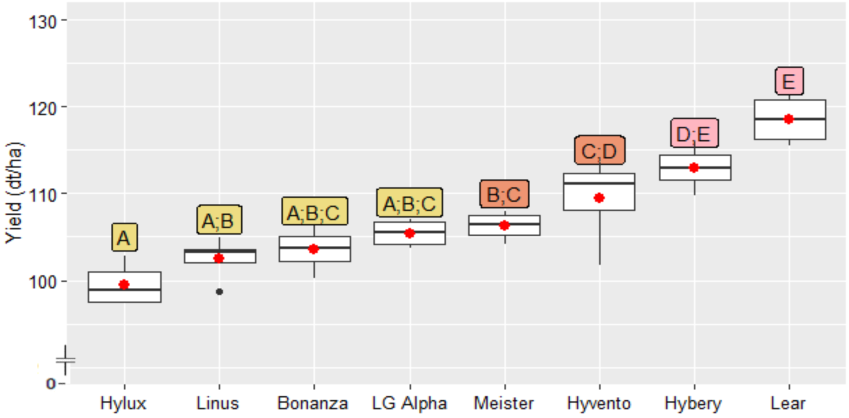

Figure 20: Yield comparison (dt/ha) of the cultivars (*p*<0.001), Giessen 2018. The lines show the scattering range, the black point the out-layer, the letters above the cld and the red points the mean.

No homogeneity of variances in the CT data and the missing of a second sowing timing in 2018, meant that an ANOVA could not utilized to compare hybrid and line cultivars. As a result, a Welch's t-test was performed. The test revealed significant yield differences between hybrid and line cultivars (*p*=0.009). In the mean hybrid cultivars outperformed line cultivars with 5 dt/ha (Figure 21).

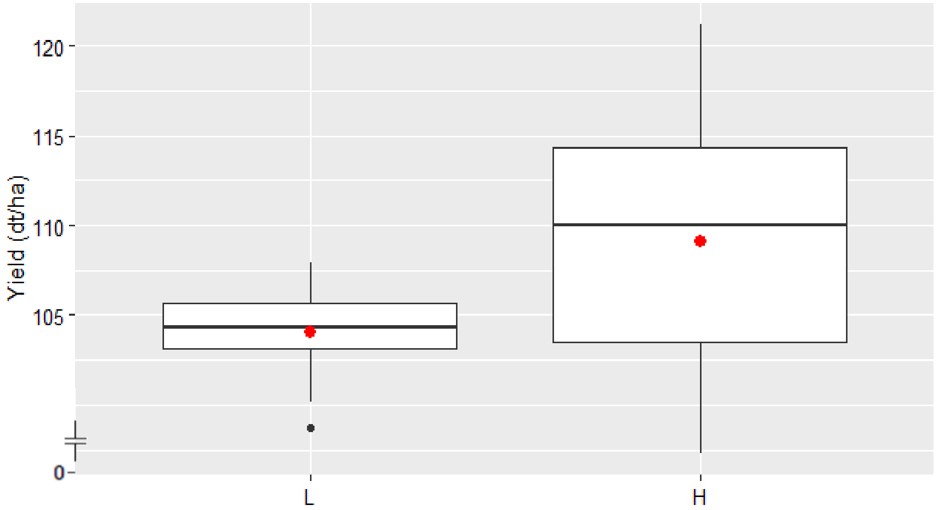

Figure 21: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 4 lines), *p*-value$_{(CT)}$ = 0.009, Giessen 2018. The lines show the scattering range and the black point indicates the out-layer.

4.1.8 Year 2019

The data set for the ANOVA in 2019 included nine different wheat cultivars in combination with two different sowing times. According to the first ANOVA, the grain yield of wheat cultivars was significantly different (*p*<0.001), and significant differences between the sowing times (*p*<0.001) were found. However, there were no significant differences in interactions between cultivars (CV) x sowing times (ST) (*p*=0.058) (Table 25).

Table 25: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Giessen, 2019.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	24.35	24.35	1	4.0481	0.181
Cultivars (CV)	717.6	89.7	8	14.9129	< 0.001
Sowing time (ST)	395.72	395.72	1	65.7891	< 0.001
CV × ST	99.03	12.38	8	2.0581	0.058

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

Hybery had the highest grain yield (93.6 dt/ha), however it was only significantly different from Meister (88.9 dt/ha) and Tabasco (82.3 dt/ha) (Figure 22). All other cultivars (lines and hybrids) show the same yield performance.

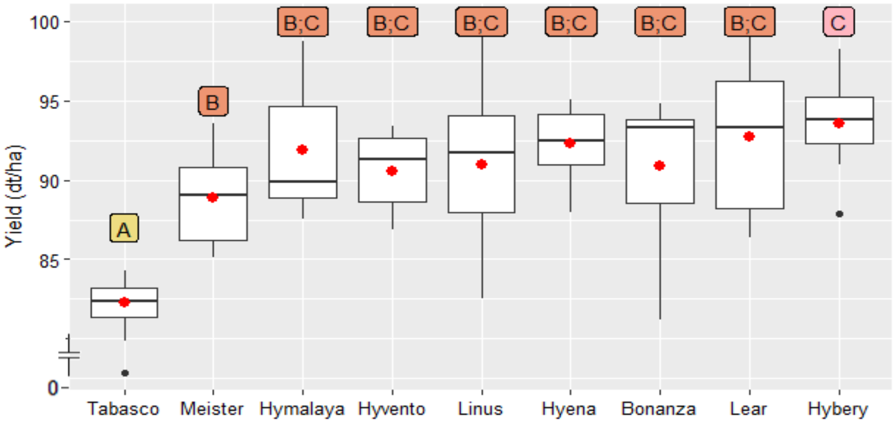

Figure 22: Yield comparison (dt/ha) of the cultivars ($p<0.001$), Giessen 2019. The lines show the scattering, the black point the out-layer, the letters above the cld and the red points the mean.

In the second ANOVA performed on the data, no interactions between CT x ST were found ($p=0.998$). The hybrid cultivars were in average significant higher yielding than the line cultivars ($p=0.002$) (Figure 23, Table 26). In the mean of the sowing times, the yield superiority amounted to 3 dt/ha.

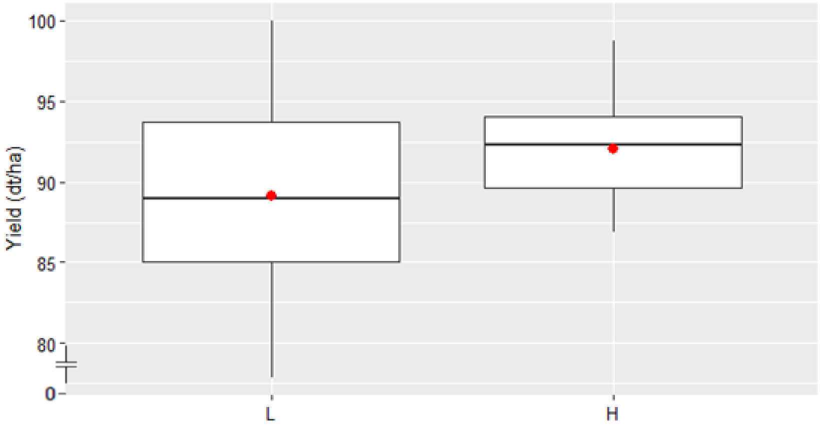

Figure 23: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines), $p\text{-value}_{(CT)} = 0.002$, Giessen 2019. The lines show the scattering range and the black point indicates the out-layer.

Table 26: Two-way ANOVA of grain yields depending on cultivars (line vs. hybrid) and sowing times, Giessen, 2019.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	60.53	60.53	1	4.0482	0.181
Cultivar type (hybrids/lines) (CT)	151.42	151.42	1	10.1263	0.002
Sowing time (ST)	390.86	390.86	1	26.1383	< 0.001
Hybrids / Lines × ST	0.0	0.0	1	0.0000	0.998

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

4.1.9 Yield comparisons for the total period 2012 to 2019

The data set used for the overview and correlations included all data from Giessen 2012-2019. In six of the eight years between 2012 and 2019, hybrid cultivars achieved higher mean grain yields than line cultivars. The grain yield of the hybrids did not differ significantly from the grain yield of the lines in the years 2014 and 2017. In 2017, were no significant variations in yield between hybrid and line cultivars, however three hybrid and one line cultivar (Hybery, Hyvento, Hyland and Linus) had the highest grain yield. Hybrid cultivars had an 8 percent better grain yield than line cultivars on average. The later sowing times resulted in higher grain yield performances of hybrid cultivars in 2013 and 2015, whereas the lines yielded more in the earlier sowing times (Table 27).

Table 27: Overview of grain yields among cultivars (hybrid vs. line) Giessen 2012-2019.

Year	*p*-value	Mean yield Lines (dt/ha) (100%)	Mean yield Hybrids (dt/ha)	Cultivars with the highest yield
2012	<0.001	69.5	86.8 (125%)	Hymack, Hybery, Hybred
2013	<0.001	94.8	99.9 (105%)	Hybery, Lear, Hystar
2014	0.150	108.2	109.8 (102%)	Hybery, Linus, Meister
2015	<0.001	70.5	78.1 (111%)	Hymack, Lear, Hyland
2016	<0.001	94.1	102.2 (109%)	Hyland, Hylux, Hystar
2017	0.959	78.9	78.8 (100%)	Hybery, Hyvento, Linus
2018	0.009	104.1	109.1 (105%)	Lear, Hystar, Hyvento
2019	0.002	89.2	92.1 (103%)	Hybery, Lear, Bonanza

4.1.10 Correlation between number of days (NOD) and grain yields in the period 2012 to 2019

The number of days were counted from different periods. Table 28 depicts a correlation matrix in which the yield compared to the: (i) total number of days (NOD) during the cropping season, (ii) from sowing to December, and (iii) January through harvest.

Table 28: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) and the growth phases of wheat plants total number of days from sowing to 31 December (NOD Sow-Dec), number of days from 01 January to harvest (NOD Jan-Harv) in Giessen 2012-2019.

Parameter	GYH	GYL	GYD	TNOD	NOD Sow-Dec	NOD Jan- Harv
GYH	-					
GYL	0.945***	-				
GYD	-0.056	-0.379	-			
TNOD	0.144	0.346	-0.651*	-		
NOD Sow-Dec	0.027	0.190	-0.504	0.873***	-	
NOD Jan- Harv	0.242	0.343	-0.365	0.373	-0.127	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

The difference in yield means of the cultivar types and the total number of days had a negative correlation (*r*=-0.651*), indicating that the more days in the cropping season, the less difference in yield means between the hybrid and line cultivars. Furthermore, the total NOD from sowing to December demonstrated a stronger correlation (*r*=-0.504) with the yield difference than the total NOD from January to harvest (*r*=-0.365). It means that the time for tillering before winter had a bigger influence on the line cultivars than on the hybrid cultivars in aspect of grain yield.

Table *29* depicts the effect of the NOD <0°C, <5°C, and >5°C. According to the data it was observed that the yield difference was influenced by the NOD over 5°C. The yield difference between hybrid and line cultivars was lower the more days over 5°C in the cropping season (*r*=-0.561).

Table 29: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields of line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) and the number of days <0 °C (NOD<0), number of days <5 °C (NOD<5) and number of days >5 °C (NOD>5) in Giessen 2012-2019.

Parameters	GYH	GYL	GYD	NOD<0	NOD<5	NOD>5
GYH	-					
GYL	0.945***	-				
GYD	-0.056	-0.379	-			
NOD<0	-0.256	-0.204	-0.102	-		
NOD<5	-0.246	-0.237	-0.027	0.798***	-	
NOD>5	0.282	0.445	-0.561*	-0.424	-0.563*	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

The influence of the NOD above 5°C considered further in Table 30. The NOD over 5°C had a closer correlation (*r*=-0.409) for the time from January to harvest than the NOD over 5°C from sowing to December (*r*=-0.261). Nonetheless, none of them was significant.

Table 30: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields of line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) and the number of days >5°C (NOD>5), number of days >5°C from sowing to 31 December (NOD>5 Sow-Dec), number of days >5°C from 01 January to harvest (NOD>5 Jan-Harv) in Giessen 2012-2019.

Parameters	GYH	GYL	GYD	NOD>5	NOD>5 Jan- Harv	NOD>5 Sow-Dec
GYH	-					
GYL	0.945***	-				
GYD	-0.056	-0.379	-			
NOD>5	0.282	0.445	-0.561*	-		
NOD>5 Jan- Harv	0.232	0.349	-0.409	0.635*	-	
NOD>5 Sow-Dec	0.103	0.181	-0.261	0.566*	-0.278	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

Table 31 presents the effect of the NOD at temperatures over 10°C, 15°C, and 20°C. The NOD over 20°C had the most association to the yield difference (*r*=-0.555*). The yield difference was lower the more days above 20°C. The yield of the hybrid cultivars was not affected by any NOD. However, the NOD over 10°C, as well as the NOD over 15°C (*r*=0.587*), showed a strong positive correlation (*r*=0.537*) with the grain yield of the lines. Even though none of them was significant, the influence of the NOD over 20°C on the grain yield of line cultivars was higher (*r*=0.413) than on the grain yield of hybrid cultivars (*r*=0.249).

Table 31: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields of line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) and the number of days >10°C (NOD>10), number of days >15°C (NOD>15), number of days >20 °C (NOD>20) in Giessen 2012-2019.

Parameters	GYH	GYL	GYD	NOD>10	NOD>15	NOD>20
GYH	-					
GYL	0.945***	-				
GYD	-0.056	-0.379	-			
NOD>10	0.441	0.537*	-0.393*	-		
NOD>15	0.472	0.587*	-0.458	0.577*	-	
NOD>20	0.249	0.413	-0.555*	0.080	0.420	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

4.1.11 Correlation between precipitation (PPT) and grain yields in the period 2012 to 2019

The impact of the PPT from sowing to August, the PPT from March to August, and the PPT from May to August was investigated. The precipitation from March to August had a substantial negative correlation with the yield difference (*r*=-0.578*). The greater the precipitation during this period, the less the yield advantage of the hybrid compared to line cultivars (Table 32).

Table 32: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields of line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) and the mount of precipitation from Sowing to August (PPT Sow-Aug), and the mount of precipitation from March to August (PPT Mar-Aug), and the mount of precipitation from May to August (PPT May-Aug) in Giessen 2012-2019.

Parameter	GYH	GYL	GYD	PPT Sow-Aug	PPT Mar-Aug	PPT May-Aug
GYH	-					
GYL	0.945***	-				
GYD	-0.056	-0.379	-			
PPT Sow-Aug	0.314	0.439	-0.451*	-		
PPT Mar-Aug	0.158	0.335*	-0.578*	0.955***	-	
PPT May-Aug	0.073	0.237	-0.518	0.922***	0.985***	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

4.1.12 Correlation between global radiation (GR) and grain yields in the period 2012 to 2019

Table *33* shows the influence of the global radiation (GR) in kWh/m^2 on the grain yield and grain yield difference. The GR in the cropping season was most closely related to the grain yield difference (GYD) between hybrid and line cultivars (*r*=-0.732**). Higher GR reduced the grain yield advantage of the hybrid cultivars.

Parameter	GYH	GYL	GYD	GR (kWh/m^2)	GR (kWh/m^2) Mar-Harv
GYH	-				
GYL	0.945***	-			
GYD	-0.056	-0.379	-		
GR (kWh/m^2)	0.054	0.289	-0.732**	-	
GR (kWh/m^2) Mar-Harv	0.103	0.264*	-0.514	0.753**	-

Table 33: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields of line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) and the Global radiation (GR (kWh/m^2)) amount and global radiation from March to harvest (GR (kWh/m^2) Mar-Harv) in Giessen 2012-2019.

Parameter	GYH	GYL	GYD	GR (kWh/m^2)	GR (kWh/m^2) Mar-Harv
GYH	-				
GYL	0.945***	-			
GYD	-0.056	-0.379	-		
GR (kWh/m^2)	0.054	0.289	-0.732**	-	
GR (kWh/m^2) Mar-Harv	0.103	0.264*	-0.514	0.753**	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

Table 34 shows the grain yield differences of the first (S1) and second (S2) sowing times in hybrids were not significantly correlated with the grain yield differences of S1 and S2 in line cultivars (*r*=0.594).

Table 34: Pearson correlation coefficients (r) between the parameters: grain yield difference (first sowing time minus second sowing time) of hybrids (GYDH (S1 to S2)) and lines (GYDL (S1 to S2)) and the global radiation (GR (kWh/m^2)) amount and global radiation from March till harvest (GR (kWh/m^2) Mar-Harv in Giessen 2012-2019.

Parameter	GYDH (S1 to S2)	GYDL (S1 to S2)	GR (kWh/m^2)	GR (kWh/m^2) Mar-Harv
GYDH (S1 to S2)	-			
GYDL (S1 to S2)	0.594	-		
GR (kWh/m^2)	0.551	0.341	-	
GR (kWh/m^2) Mar-Harv	0.376	0.587	0.821*	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

4.2 Yield comparisons of the wheat cultivars in Gross Gerau

4.2.1 Year 2012

In Gross Gerau 2012, the data set for the analysis of variance (ANOVA) consisted of nine wheat cultivars (CV) in combination with three different sowing timings. Two evaluations were carried out on the data to test for possible variety x sowing time interactions: (1) Firstly, all eight varieties were included and their reaction to sowing time was tested (interaction varieties x sowing time). (2) Secondly, only the two cultivar types (line vs. hybrid varieties) were examined with regard to their reaction to sowing time (interaction cultivar type x sowing time).
According to the ANOVA, the grain yield of wheat cultivars was significantly different ($p<0.001$), also significant differences were found between the sowing times ($p<0.001$). However, no significant interactions between cultivars (CV) x sowing times (ST) were found (p=0.579) (Table 35).

Table 35: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Gross Gerau, 2012.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	17.7	17.7	1	1.1936	0.388
Cultivars (CV)	683.71	85.46	8	5.7642	< 0.001
Sowing time (ST)	2066.17	1033.09	2	69.6779	< 0.001
CV × ST	211.83	13.24	16	0.8929	0.579

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

Hybery (78.2 dt/ha) and Tabasco (69.4 dt/ha) had the highest and lowest yield, respectively. The yield of Hybery was significantly higher than the other cultivars. In addition, except for Hybery, all cultivars produced a comparable amount of grain yield (Figure 24).

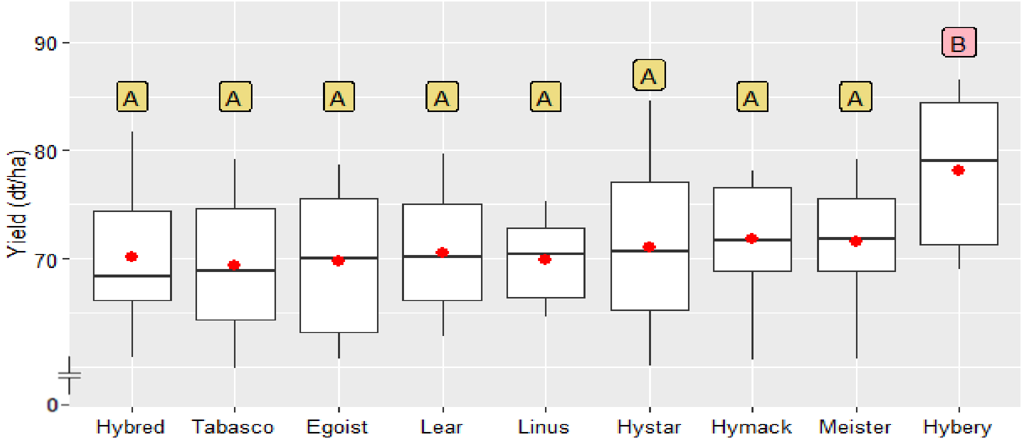

Figure 24: Yield comparison (dt/ha) of the cultivars ($p<0.001$), Gross Gerau 2012. The lines show the scattering range, the black point the out-layer, the letters above the cld and the red points the mean.

The second evaluation of the data, showed no significant interaction between CT x ST. However, using a t-Test to compare the grain yield of the CT, a significant difference between hybrid and line cultivars was found (*p*=0.046) (Figure 25). Line cultivars yielded 70.3 dt/ha on average, which was comparable to hybrid cultivars yield of 72.8 dt/ha.

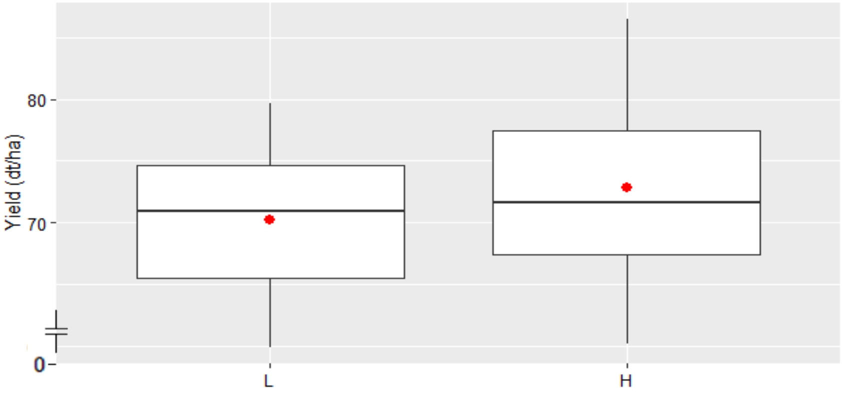

Figure 25: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines), *p*-value$_{(CV)}$ <0.001, Gross Gerau 2012. The lines show the scattering range and the black point indicates the out-layer.

Figure 26 compares the yields of three different sowing times. According to the data, the third sowing time provided the highest mean yield (76.1 dt/ha), followed by the second (72.5 dt/ha) and the first sowing (65.6 dt/ha). All of the sowing times were significantly different from each other (*p*<0.001).

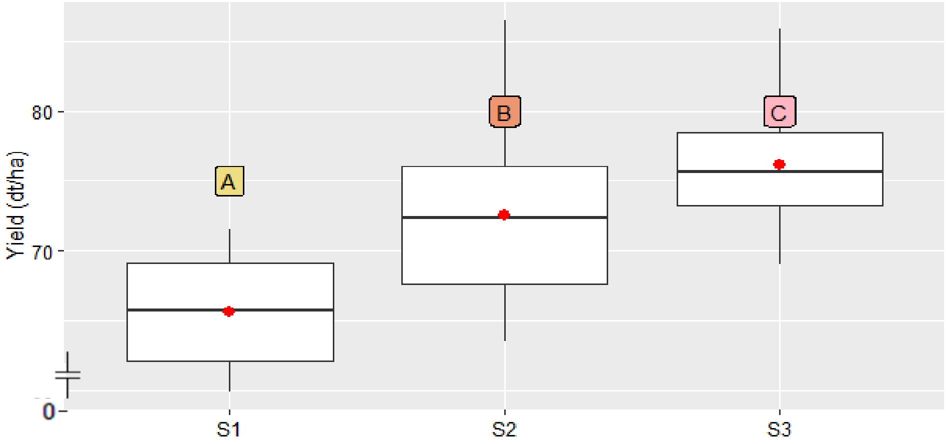

Figure 26: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines), *p*-value$_{(ST)}$ <0.001, Gross Gerau 2012. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 medium, S3 late sowing time.

4.2.2 Year 2013

The data set for the ANOVA in 2013 included nine different cultivars in combination with three different sowing times. According to the first ANOVA, the grain yield of the cultivars was significantly different (p<0.001), also in the sowing times significant differences (p<0.001) were found. However, there were no significant interactions between CV x ST (p=0.920) (Table 36). This result confirms that the CV do not react differently in different sowing times.

Table 36: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Gross Gerau, 2013.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	167.97	167.96	1	12.9012	0.069
Cultivars (CV)	1339.42	167.428	8	12.8599	< 0.001
Sowing time (ST)	301.49	150.743	2	11.5783	< 0.001
CV × ST	111.4	6.962	16	0.5348	0.92

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

The hybrid cultivars (Hystar, Hybred, Hymack and Hybery) surpass line cultivars in terms of grain yield, beside Lear (93.9 dt/ha) (Figure 27).

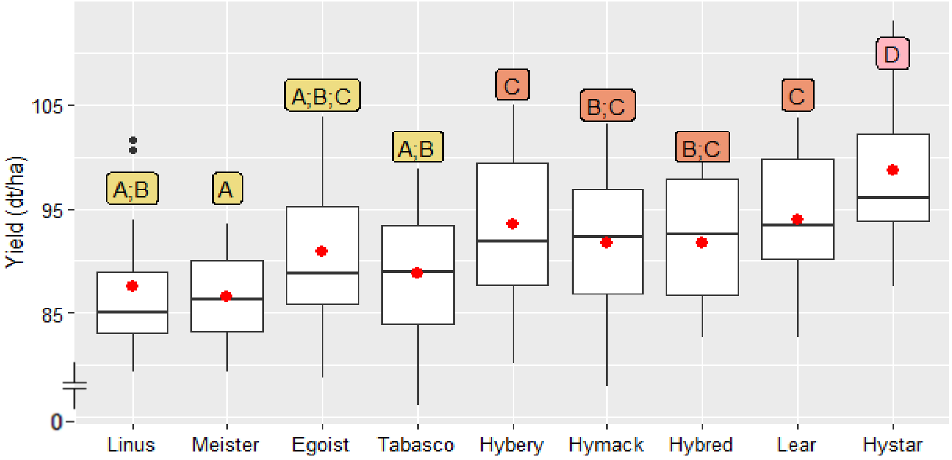

Figure 27: Yield comparison (dt/ha) of the wheat cultivars (p<0.001), Gross Gerau 2013. The lines show the scattering range and the black point indicates the out-layer.

Hybrid and Line cultivars showed significant differences in the grain yield (*p*<0.001). The hybrid cultivars had a higher mean grain yield (93.9 dt/ha), compared to the line cultivars (89.5 dt/ha) (Figure 28).

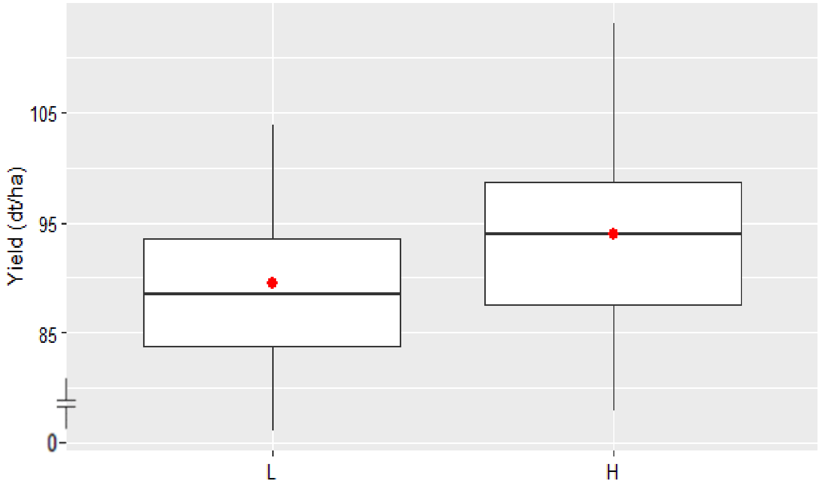

Figure 28: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines), *p*-value$_{(CV)}$ <0.001, Gross Gerau 2013. The lines show the scattering range and the black point indicates the out-layer.

Delayed sowing led to a reduction in grain yield of all cultivars, but the variation between the CVs were high. Significant differences between them were determined (*p*<0.001). The third sowing time had a lower average yield (89.1 dt/ha) and a higher variance than the second and third sowing times (92.5 dt/ha and 92.8 dt/ha, respectively). It shows that the variations across cultivars are most noticeable during the third sowing time in 2013 (Figure 29).

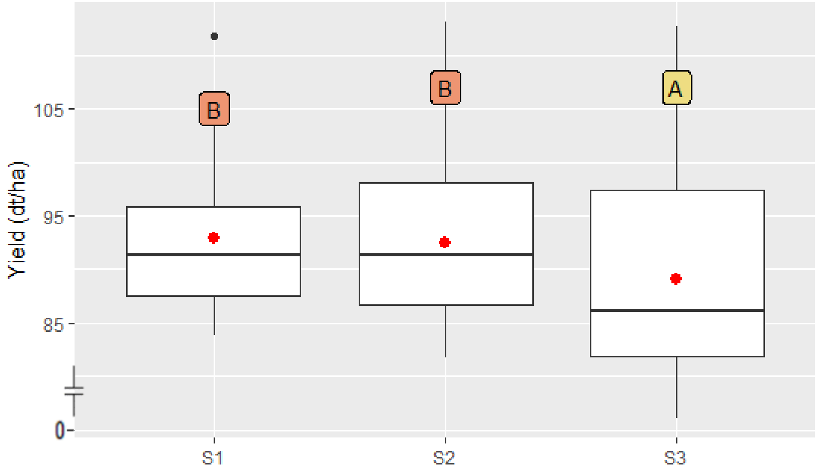

Figure 29: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines), *p*-value$_{(ST)}$ <0,001 , Gross Gerau 2013. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 medium, S3 late sowing time.

4.2.3 Year 2014

The data set for the ANOVA in 2014 included nine different wheat cultivars in combination with three different sowing times. According to the first ANOVA, the grain yield of the cultivars was significantly different (*p*<0.001). The sowing times showed significant differences (*p*<0.001). However, there were no significant interactions between cultivars x sowing times (*p*=0.622) (Table 37).

Table 37: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Gross Gerau, 2014.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	487.9	487.94	1	10.819	0.081
Cultivars (CV)	4310.6	538.83	8	11.9484	< 0.001
Sowing time (ST)	615.8	307.92	2	6.8279	0.001
CV × ST	615.8	38.49	16	0.8535	0.622

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

There were no significant differences between the cultivars in aspect of grain yield except Hystar (82.5 dt/ha) and Egoist (78.0 dt/ha) which show significantly higher grain yield (*p*<0.001). but significantly more than Tabasco (71.0 dt/ha) (Figure 30).

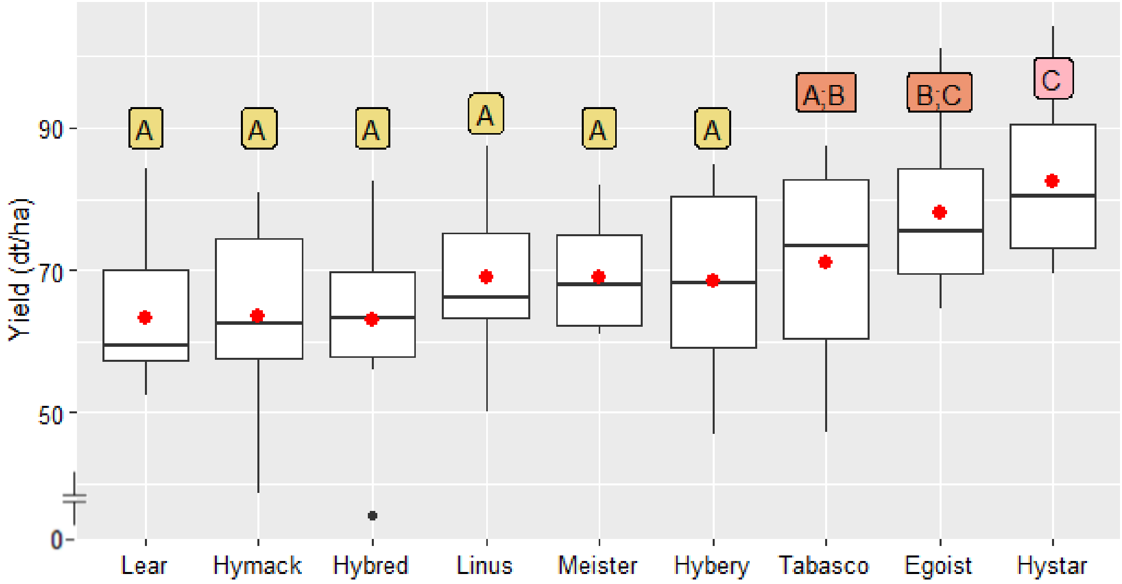

Figure 30: Yield comparison (dt/ha) of the wheat cultivars (*p*<0.001), Gross Gerau 2014. The lines show the scattering range and the black point indicates the out-layer.

The second ANOVA showed no interaction between CT x ST (*p*=0.579). However, the sowing times showed significant differences (*p*=0.031). No significant differences were found between the hybrid and line cultivars (Table 38).

Table 38: Two-way ANOVA of grain yields depending on cultivars (line vs. hybrid) and sowing times, Gross Gerau, 2014.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	911.46	911.46	1	10.82	0.081
Cultivar type (hybrids/lines) CT	11.84	11.84	1	0.1405	0.709
Sowing time (ST)	605.37	302.68	2	3.5932	0.031
Hybrids / Lines × ST	92.58	46.29	2	0.5495	0.579

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

Delaying sowing time led to a significant reduction in grain yield of cultivars (Figure 31). The third (66.4 dt/ha) sowing time had 5 dt/ha less grain yield compared to the first (71.3 dt/ha) and second (71.7 dt/ha) sowing time.

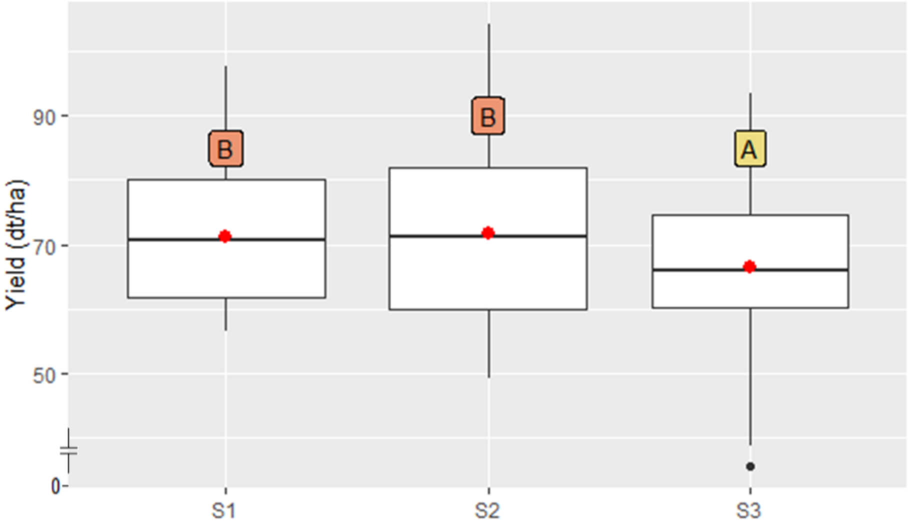

Figure 31: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines), *p*-value$_{(ST)}$ = 0,001, Gross Gerau 2014. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 medium, S3 late sowing time.

4.2.4 Year 2015

The data set for the ANOVA in 2015, included nine different wheat cultivars in combination with three different sowing times. According to first ANOVA, the grain yields of wheat cultivars were significantly different (*p*=0.009). In the three different sowing times significant differences (*p*<0.001) were found. There were no significant interactions between CV x ST (*p*=0.108) (Table 39).

Table 39: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Gross Gerau, 2015.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	15.63	15.63	1	0.425	0.581
Cultivars (CV)	814.55	101.82	8	2.7688	0.009
Sowing time (ST)	1379.57	689.78	2	18.7574	< 0.001
CV × ST	915.66	57.23	16	1.5562	0.108

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

The cultivars did not show significant differences to each other expect Hystar (*p*=0.009). Three of four hybrid cultivars (Hystar, Hybery and Hyland) showed a higher median yield compared to line cultivars in terms of grain yield except Lear. Hybred showed a lower median yield, however, the mean yield was as high as the other hybrid cultivars, that was caused by the high variance between the reputation (Figure 32).

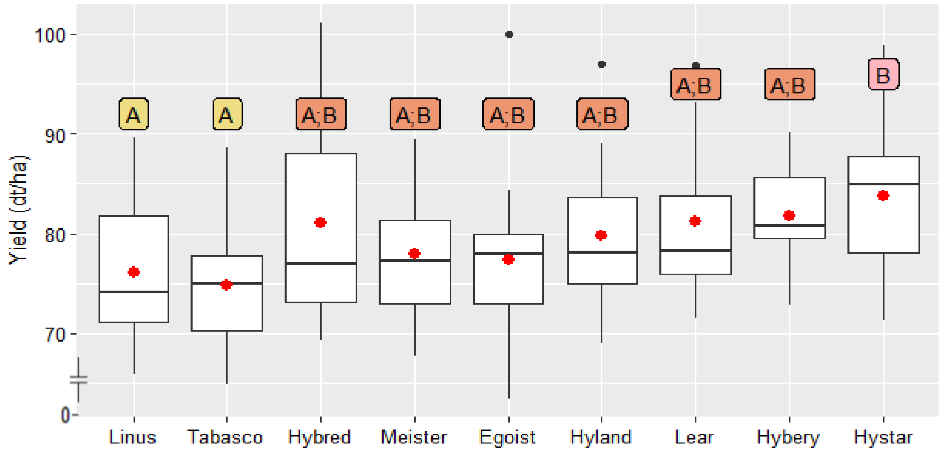

Figure 32:Yield comparison (dt/ha) of the wheat cultivars (*p*=0.009), Gross Gerau 2015. The lines show the scattering range and the black point indicates the out-layer.

The second ANOVA performed on the data, showed no significant interaction between CT x ST. However, significant differences between hybrid and line cultivars (*p*<0.001) were found. Also, significant differences between the sowing times (*p*<0.001) were found (Table 40).

Table 40: Two-way ANOVA of grain yields depending on cultivars (line vs. hybrid) and sowing times, Gross Gerau, 2015.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	16.9	16.9	1	0.425	0.581
Cultivar type (hybrids/lines) CT	438.21	438.21	1	11.0169	< 0.001
Sowing time (ST)	1312.99	656.49	2	16.5047	< 0.001
Hybrids / Lines × ST	222.53	111.27	2	2.7973	0.066

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

For both cultivar types (hybrids and lines) delayed sowing time caused reduction in the grain yield. However, this reduction was less for hybrids compared to line cultivars. In the first sowing time both cultivar types showed the same grain yield (83 dt/ha), while in the third sowing time the hybrid cultivars superiority amounted 2 dt/ha compared to the line cultivars. The highest grain yield differences (8 dt/ha) between the cultivar types were recorded in the second sowing time (Figure 33).

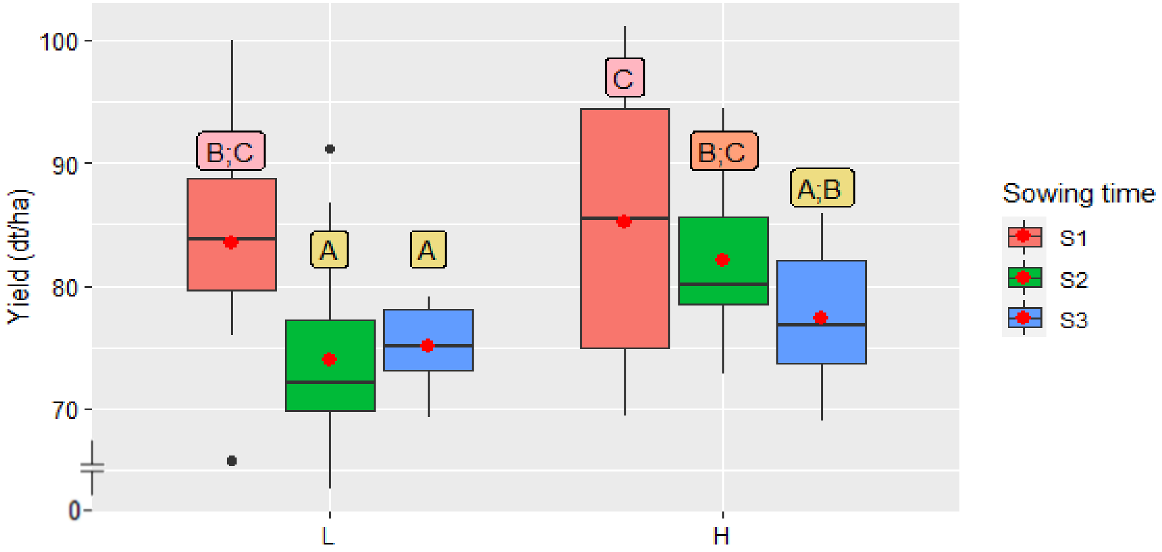

Figure 33: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines), *p*-value$_{(CVxST)}$ = 0.066), Gross Gerau 2015. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 medium, S3 late sowing time.

4.2.5 Year 2016

The data set for the ANOVA in 2016 included nine different wheat cultivars in combination with three different sowing times. The ANOVA table showed no significant differences either for the cultivars (*p*=0.261) nor for the sowing times (*p*=0.949). However, there were significant interactions between cultivars and sowing times (*p*=0.004), which showed that the cultivars reacted differently to the sowing times (Table 41).

Table 41: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Gross Gerau, 2016.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	0.01	0.0103	1	0.003	0.961
Cultivars (CV)	35.39	4.4237	8	1.2893	0.261
Sowing time (ST)	0.362	0.1808	2	0.0527	0.949
CV × ST	135.71	8.4819	16	2.472	0.004

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

The reaction of the cultivars to the different sowing times were not similar to each other. The grain yields of Hybred and Hyland were less influenced by delayed sowing time. However, the line cultivars Meister, Lear and Egoist showed higher mean grain yield compared to the hybrid cultivars and the other line cultivars. Egoist, compared to other cultivars had the lowest yield in the first sowing time and the highest yield in the second sowing time (Figure 34). In the post-hoc analysis it was found, that between all cultivars, just Egoist showed significant differences between the first and second sowing time. The differences between the sowing times in the other cultivars were not significant (Table 42).

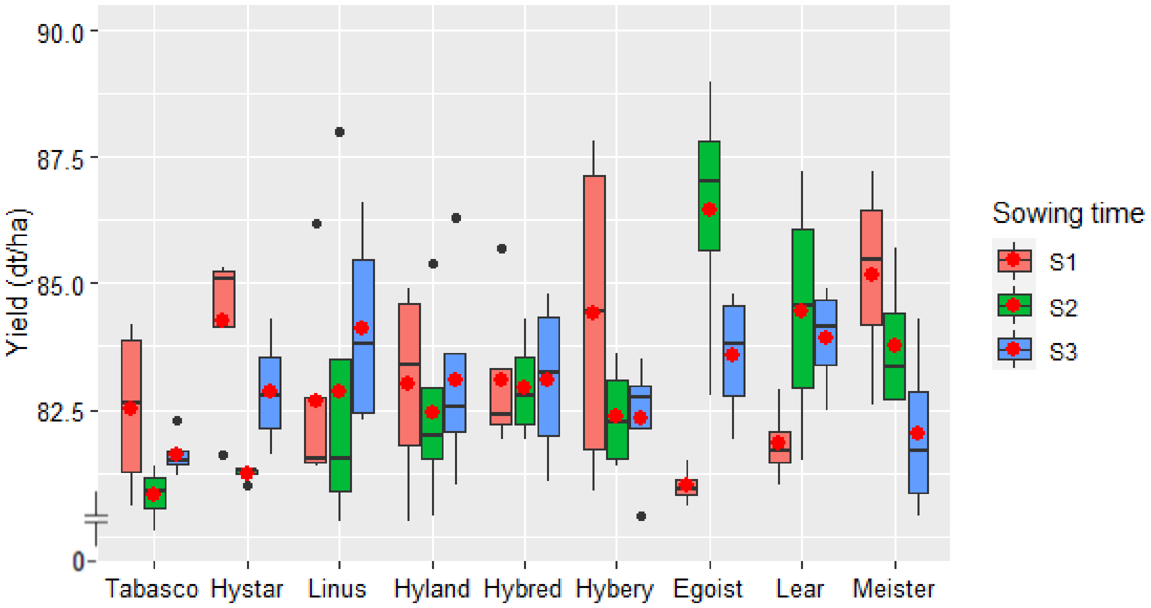

Figure 34: Yield comparison (dt/ha) of the wheat cultivars *p*-value CVxST (*p*=0.004), Gross Gerau 2016. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 medium, S3 late sowing time.

According to the results, hybrid cultivars have higher yield compatibility to the first sowing time (83.7 dt/ha) than to the second and third sowing time. On the contrary, the line cultivars presented higher yield compatibility to the second sowing times (Figure 35).

Table 42: Compact letter display of the cultivars under the influence of the sowing times, Gross Gerau 2016. SE= standard error, DF= degree of freedom, lower CI= confidence interval, group= the characters with the same letter are not significantly different from each other.

Cultivars	Sowing time	Mean	SE	DF	Lower CI	Upper CI	Group
Tabasco (L)	S2	80.8	0.933	77.8	79.0	82.7	A
Egoist (L)	S1	81.0	0.933	77.8	79.1	82.9	A
Hystar (H)	S2	81.2	0.933	77.8	79.4	83.1	A
Tabasco (L)	S3	81.6	0.933	77.8	79.8	83.5	AB
Lear (L)	S1	81.8	0.933	77.8	80.0	83.7	AB
Meister (L)	S3	82.0	0.933	77.8	80.2	83.9	AB
Hybery (H)	S3	82.3	0.933	77.8	80.5	84.2	AB
Hybery (H)	S2	82.4	0.933	77.8	80.5	84.2	AB
Hyland (H)	S2	82.5	0.933	77.8	80.6	84.3	AB
Tabasco (L)	S1	82.5	0.933	77.8	80.7	84.4	AB
Linus (L)	S1	82.7	0.933	77.8	80.8	84.5	AB
Linus (L)	S2	82.8	0.933	77.8	81.0	84.7	AB
Hystar (H)	S3	82.9	0.933	77.8	81.0	84.7	AB
Hybred (H)	S2	83.0	0.933	77.8	81.1	84.8	AB
Hyland (H)	S1	83.0	0.933	77.8	81.1	84.9	AB
Hybred (H)	S3	83.1	0.933	77.8	81.2	85.0	AB
Hyland (H)	S3	83.1	0.933	77.8	81.2	85.0	AB
Hybred (H)	S1	83.1	0.933	77.8	81.2	85.0	AB
Egoist (L)	S3	83.6	0.933	77.8	81.7	85.4	AB
Meister (L)	S2	83.8	0.933	77.8	81.9	85.6	AB
Lear (L)	S3	83.9	0.933	77.8	82.1	85.8	AB
Linus (L)	S3	84.1	0.933	77.8	82.3	86.0	AB
Hystar (H)	S1	84.3	0.933	77.8	82.4	86.1	AB
Hybery (H)	S1	84.4	0.933	77.8	82.5	86.3	AB
Lear (L)	S2	84.5	0.933	77.8	82.6	86.3	AB
Meister (L)	S1	85.2	0.933	77.8	83.3	87.0	AB
Egoist (L)	S2	86.5	0.933	77.8	84.6	88.3	B

The second ANOVA revealed significant interaction between cultivar type (hybrid vs. line) x sowing times (*p*=0.042), but the post-hoc test showed no different groups (Table 43). Also, no significant differences between CT (*p*=0.638) were found. In general hybrid cultivars showed a higher grain yield in the first sowing time compared to the lines, while the lines had a higher grain yield in the second sowing time, however, the grain yield differences between the sowing times were marginal (Figure 35).

Table 43: Two-way ANOVA of grain yield (hybrid vs. line) of cultivars and their interaction with sowing times, Gross Gerau, 2016.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	0.012	0.012	1	0.003	0.961
Cultivar type (hybrids/lines) CT	0.925	0.925	1	0.223	0.637
Sowing time (ST)	1.021	0.51	2	0.123	0.884
Hybrids / Lines × ST	27.062	13.531	2	3.261	0.042

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

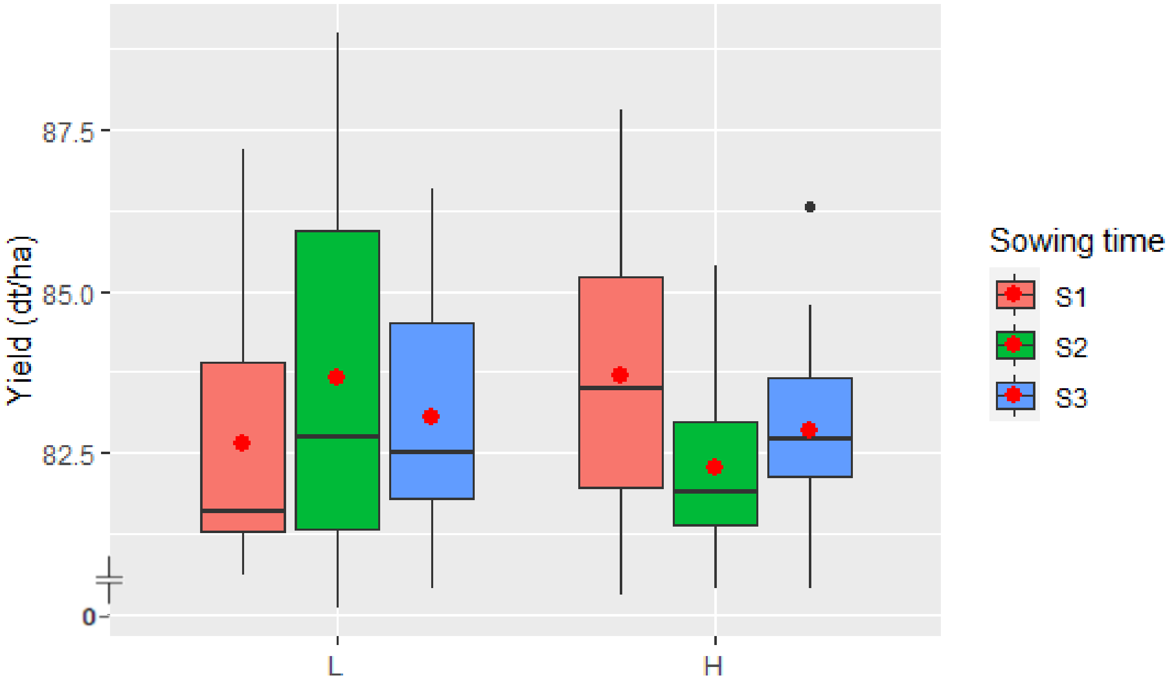

Figure 35: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines), *p*-value$_{(CVxST)}$ = 0.042, Gross Gerau 2016. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 medium, S3 late sowing time. Post-hoc test showed no significant differences.

4.2.6 Year 2017

The data set for the ANOVA in 2017 included ten different wheat cultivars in combination with two sowing times. The ANOVA table showed significantly different between the CV (*p*=0.008). There was no significant difference between the sowing times (*p*=0.466), and no significant interaction effects between the CV x ST were found (*p*=0.725) (Table 44).

Table 44: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Gross Gerau, 2017.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	173.09	173.089	1	6.0654	0.132
Cultivars (CV)	722.8	80.311	9	2.8184	0.008
Sowing time (ST)	15.4	15.4	1	0.5397	0.466
CV × ST	174.35	19.373	9	0.6789	0.725

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

Hybery (64.0 dt/ha) and Meister (64.7 dt/ha) produced significantly higher yields than Tabasco (54.9 dt/ha) among the cultivars. There was no significant difference between the other cultivars (Figure 36). Tendentially the mean of grain yield was higher for the hybrids compared to the lines, except Meister.

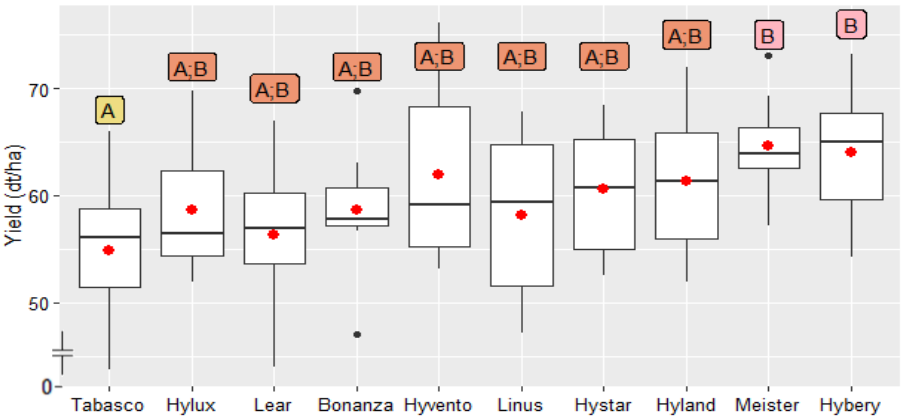

Figure 36: Yield comparison (dt/ha) of the wheat cultivars *p*-value CV (*p*=0.008), Gross Gerau 2017. The lines show the scattering range and the black point indicates the out-layer.

The second ANOVA showed significant differences between hybrid and line cultivars (*p*=0.033), but no significant differences in sowing times (*p*=0.492) or interactions between CT x ST (*p*=0.683) (Table 43). The hybrid cultivars had a mean yield of 61.3 dt/ha, the line cultivars a mean yield of 58.5 dt/ha, this resulted in 3 dt/ha grain yield superiority by hybrid cultivar. The variance of hybrid cultivars was lower (47.3) than the variance of the line cultivars (54.8) (Figure 37).

Table 43: Two-way ANOVA of grain yield (hybrid vs. line) of cultivars and their interaction with sowing times, Gross Gerau, 2017.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	196.47	196.47	1	6.0654	0.132
Cultivar type (hybrids/lines) CT	153.74	153.74	1	4.7462	0.033
Sowing time (ST)	15.4	15.4	1	0.4754	0.492
Hybrids / Lines × ST	5.46	5.46	1	0.1686	0.683

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

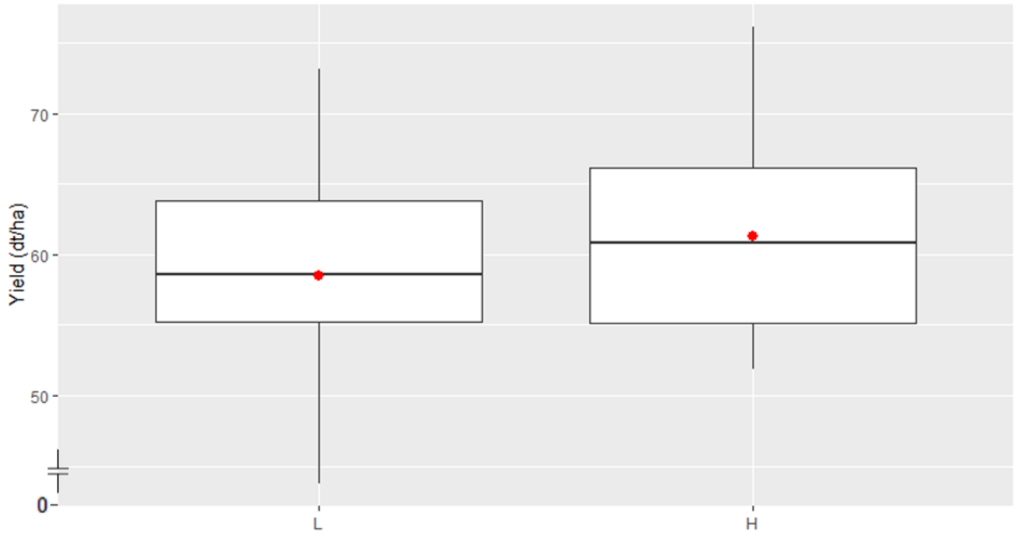

Figure 37: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines), *p*-value$_{(CT)}$ = 0.033, Gross Gerau 2017. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 medium, S3 late sowing time.

4.2.7 Year 2018

The data set for the ANOVA in 2018 included seven (two hybrids and 5 lines) different wheat cultivars examined in only one sowing time. The yields of wheat cultivars did not differ significantly (*p*=0.086) according to the ANOVA (Table 45). Line cultivars (57.1 dt / ha) outperformed hybrid cultivars (54.4 dt/ ha) in terms of average yield. This difference, however, was not statistically significant (data not shown). Meister and Bonanza had the highest and lowest yield, respectively (Figure 38). No significant difference between cultivars were found.

Table 45: ANOVA of the yield of different cultivars and sowing times, Gross Gerau, 2018.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	298.75	298.75	1	16.505	0.056
Cultivars (CV)	243.31	40.55	6	2.24	0.086

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

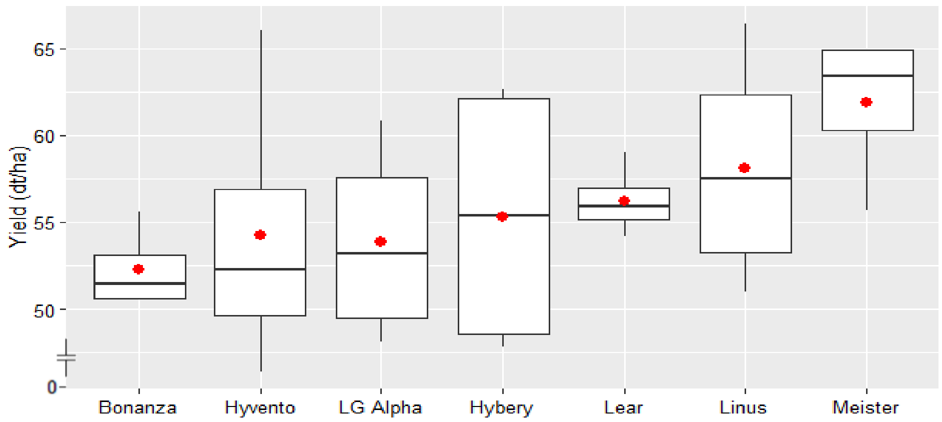

Figure 38: Yield comparison (dt/ha) of the wheat cultivars *p*-value CV (*p*=0.086), Gross Gerau 2018. The lines show the scattering range and the black point indicates the out-layer.

4.2.8 Year 2019

The ANOVA in 2019 included nine different wheat cultivars in combination with two sowing times. The first ANOVA table revealed no significant differences between the cultivars (*p*= 0.161), but significant differences between the sowing times (*p*<0.001) were observed. Furthermore, no interaction effects between cultivar x sowing times were found (*p*=0.876) (Table 46).

Table 46: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Gross Gerau, 2017.Gross Gerau, 2019.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	25.1	25.1	1	1.17	0.392
Cultivars (CV)	267.4	33.4	8	1.5575	0.161
Sowing time (ST)	4010.6	4010.6	1	186.864	<0.001
CV × ST	79.7	10	8	0.464	0.876

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

According to the second ANOVA the cultivars yielded significantly more in the first sowing time (71.4 dt/ha) than in the second sowing time (56.4 dt/ha). The delayed sowing time led to a reduction in grain yield of 15 dt/ha (Figure 39). No significant differences between hybrid and line cultivars (*p*=0.085) were found. Furthermore, there were no significant interactions between cultivar type x sowing time (*p*=0.248) (Table 47).

Table 47: Two-way ANOVA of grain yield (hybrid vs. line) of cultivars and their interaction with sowing times, Gross Gerau, 2019.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	24.3	24.3	1	1.17	0.392
Cultivar type (hybrids/lines) CT	63.5	63.5	1	3.055	0.085
Sowing time (ST)	4035.8	4035.8	1	194.312	>0.001
Hybrids / Lines × ST	28.2	28.2	1	1.359	0.248

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

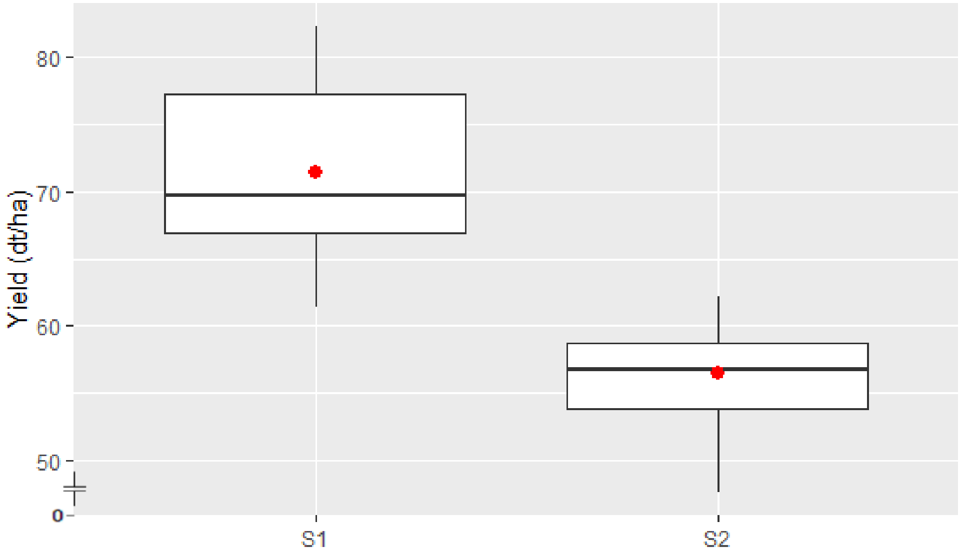

Figure 39: Yield comparison (dt/ha) of wheat cultivars (H: 4 hybrids, L: 5 lines), *p*-value$_{(ST)}$ <0.001, Gross Gerau 2019. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 late sowing time.

4.2.9 Yield comparisons for the total period 2012 to 2019

The data set used for the overview and for the correlations included all data from Gross Gerau 2012-2019. In four of eight years (2012, 2013, 2015, and 2017), a significant difference in yield between hybrid and line cultivars were found (Table 48). In contrast, in 2014, 2016 and 2019 there were no yield differences between the two types of cultivars but yield equality.

Table 48: Overview of grain yield among cultivars (hybrids and lines) Gross Gerau 2012-2019.

Year	*p*-value	Mean yield Lines (dt/ha) 100%	Mean yield Hybrids (dt/ha)	Cultivars with the highest mean yield
2012	0.046	70.3	72.8 (104%)	Hybery, Hymack, Meister
2013	<0.001	89.5	93.9 (105%)	Hystar, Lear, Hybery
2014	0.708	70.1	69.4 (99%)	Hystar, Egoist, Tabasco
2015	<0.001	75.1	77.4 (103%)	Hystar, Hybery, Lear
2016	0,638	83.1	82.9 (100%)	Meister, Lear, Egoist
2017	0.033	58.5	61.3 (105%)	Meister, Hybery, Hyvento
2018	-	57.1	54.4 (95%)	Meister, Linus, Lear
2019	0.085	63.1	65.0 (103%)	Hymalaya, Hyena, Lear

The average of the grain yield difference between hybrid and line cultivars was 1.3 dt/ha (Table 48). Comparing the mean yield level of all varieties in all years, it can be seen that the highest yield level was achieved in 2013 with 93.9 dt/ha and the lowest in 2018 with 54.4 dt/ha. It is noteworthy that the highest yields in 2013 were achieved under conditions of a long frost period (40 days <0°C).

4.2.10 Correlation between number of days (NOD) and grain yields in the period 2012 to 2019

The number of days were counted from three different periods (sowing till harvest, sowing till December and January till harvest) and were correlated with the grain yield of the cultivar types, grain yield hybrids (GYH) and grain yield lines (GYL) and the yield differences between them (GYD). The highest grain yield in Gross Gerau was reached in the coldest year 2013. It was the year with the most NOD with temperatures below 5°C (115 days), and the less days over 5°C (S1: 181 days, S2: 157 days). Between the sowing date and December, 2015 and 2017 had the fewest NOD under 5 °C. In addition, from March till harvest, 2015 was the driest year on record (139.2 mm). 2015 was also the year with the lowest grain yield in Gross Gerau. In 2013, 2014, 2015, and 2019, earlier sowing yielded more than later sowing, only in 2012 a higher grain yield in the later sowing time were found. In the other years were no significant differences found between the sowing times. Table 49 shows a correlation-matrix comparing yield to NOD throughout the cropping season, from sowing to December, and the total NOD from January to harvest. There was no significant correlation between the difference in yield means and the total number of days (*r*= 315).

Table 49: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) and the growth phases of wheat plants total number of days from sowing to 31 December (NOD Sow-Dec), number of days from 01 January to harvest (NOD Jan-Harv) in Gross-Gerau 2012-2019.

Parameter	GYH	GYL	GYD	TNOD	NOD Sow-Dec	NOD Jan- Harv
GYH	-					
GYL	0.989***	-				
GYD	0.567	0.437	-			
TNOD	0.216	0.179	0.315	-		
NOD Sow-Dec	0.192	0.116	0.512	0.262	-	
NOD Jan- Harv	0.134	0.130	0.091	0.902***	-0.181	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

Table 50 depicts a correlation Matrix of grain yield and yield difference in relation to NOD <0°C, <5°C, and >5°C. The result shows a significant positive correlation (*r*=0.573*) between the NOD <0 °C and the yield difference (GYD) between both cultivar types. The more NOD <0°C, the higher was the yield difference. The results of the correlation showed a grain yield advantage for the hybrids compared to the lines, the more the plants were exposed to temperatures below 0°C.

Table 50: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields of line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) and the number of days <0°C (NOD<0), number of days <5°C (NOD<5) and number of days >5°C (NOD>5) in Gross-Gerau 2012-2019.

Parameters	GYH	GYL	GYD	NOD<0	NOD<5	NOD>5
GYH	-					
GYL	0.989***	-				
GYD	0.567*	0.437	-			
NOD<0	0.137	0.045	0.573*	-		
NOD<5	0.474	0.426	0.506	0.683***	-	
NOD>5	-0.226	-0.213	-0.188	-0.402	-0.756***	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

The NOD >5°C from January to harvest was negatively correlated with grain yield of hybrids (*r*=-0.564*) and lines (*r*=-0.563*) (Table 51). This means that with increasing length of the growing season (vegetation period >5°C) the grain yields of the varieties decrease.

Table 51: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields of line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) an the number of days >5°C (NOD>5), number of days >5°C from sowing to 31 December (NOD>5 Sow-Dec), number of days >5°C from 01 January to harvest (NOD>5 Jan-Harv) in Gross-Gerau 2012-2019.

Parameters	GYH	GYL	GYD	NOD>5	NOD>5 Jan- Harv	NOD>5 Sow-Dec
GYH	-					
GYL	0.989***	-				
GYD	0.567*	0.403	-			
NOD>5	-0.226	-0.213	-0.188	-		
NOD>5 Jan- Harv	-0.564*	-0.563*	-0.286	0.752**	-	
NOD>5 Sow-Dec	0.234	0.250	0.032	0.703**	0.068	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

The grain yield of both cultivar types correlated negative with the NOD >15°C (hybrids r=-0.716** and lines r=-0.716**) and the NOD >20°C (hybrids *r*=-0.644** and lines *r*=-0.683**) (Table 52). The more warm days there were during the cropping season, the lower the grain yield was for both cultivar types.

Table 52: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields of line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) and the number of days >10°C (NOD>10), number of days >15°C (NOD>15), number of days >20°C NOD>20) in Gross-Gerau 2012-2019.

Parameters	GYH	GYL	GYD	NOD>10	NOD>15	NOD>20
GYH	-					
GYL	0.989***	-				
GYD	0.567*	0.437	-			
NOD>10	-0.297	-0.360	0.193	-		
NOD>15	-0.716**	-0.720**	-0.341	0.510	-	
NOD>20	-0.644**	-0.683**	-0.111	0.159	0.643**	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

4.2.11 Correlation between precipitation (PPT) and grain yields in the period 2012 to 2019

A significant positive correlation between grain yield of line cultivars (GYL) and precipitation from January till August (r=0.526*) were found (Table 53). The grain yield was less influenced by the precipitation in comparison with the temperatures (Table 52, Table 53), as only the precipitation from January till August had an influence to the grain yield of line cultivars. This concluded the effect of winter precipitation on the grain yield performances of the line cultivars.

Table 53: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields of line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) and the mount of precipitation from Sowing to August (PPT Sow-Aug), and the mount of precipitation from March to August (PPT Mar-Aug), and the mount of precipitation from May to August (PPT May-Aug) in Gross Gerau 2012-2019.

Parameter	GYH	GYL	GYD	PPT Jan-Aug	PPT Mar-Aug	PPT May-Aug
GYH	-					
GYL	0.989***	-				
GYD	0.567*	0.437	-			
PPT Jan-Aug	0.488	0.526*	0.040	-		
PPT Mar-Aug	0.388	0.393	0.167	0.953***	-	
PPT May-Aug	0.335	0.317	0.268	0.850***	0.928***	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

4.2.12 Correlation between global radiation (GR) and grain yields in the period 2012 to 2019

There was no significant correlation between global radiation and the yield differences between hybrids and lines in Gross Gerau, as shown in Table 54. Furthermore, global radiation was not significantly correlated with the yield of cultivars although there tended to be a negative correlation with yields and a positive correlation with yield differences.

Table 54: Pearson correlation coefficients (r) between the parameters of grain yields hybrids (GYH), grain yields of line cultivars (GYL), grain yield differences between hybrids and line cultivars (GYD) and the global radiation (GR (kWh/m²)), amount and Global radiation from March to harvest (GR (kWh/m²) Mar-Harv) in Gross Gerau 2012-2019.

Parameter	GYH	GYL	GYD	GR (kWh/m²)	GR (kWh/m²) Mar-Harv
GYH	-				
GYL	0.994***	-			
GYD	0.135	0.023	-		
GR (kWh/m²)	-0.395	-0.445	0.407	-	
GR (kWh/m²) Mar-Harv	-0.437	-0.465	0.214	0.588*	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

Table 55 shows that the yield differences of S1 and S2 in hybrids (GYDH S1 to S2) were significantly positively correlated with the yield differences of S1 and S2 in line cultivars (GYDL S1 to S2) (r=0.972***). The yield difference between the early and late sowing time was higher, the more global radiation between March and harvest was measured. The higher the global radiation in this period, the more suitable early sowing was for a high grain yield.

Table 55: Pearson correlation coefficients (r) between the parameters: grain yield difference (first sowing time minus second sowing time) of hybrids and lines and the global radiation (GR (kWh/m²)) amount and global radiation from March till harvest (GR (kWh/m²) Mar-Harv) in Gross-Gerau 2012-2019.

Parameter	GYDH (S1 to S2)	GYDL (S1 to S2)	GR (kWh/m²)	GR (kWh/m²) Mar-Harv
GYDH (S1 to S2)	-			
GYDL (S1 to S2)	0.972***	-		
GR (kWh/m²)	0.421	0.364	-	
GR (kWh/m²) Mar-Harv	0.821*	0.814*	0.610	-

Notes: The null hypothesis "there is no correlation" can be rejected with an error probability of * = 5%, ** = 1% and *** = 0.1%.

4.3 Yield comparisons of the wheat cultivars in Rauischholzhausen

4.3.1 Year 2016

The data set for the ANOVA in 2016 included ten line-cultivars, in combination with two sowing times, and four replications. Compared to Giessen or Gross Gerau, the test design in Rauischholzhausen has only limited possibilities for long-term analysis.

According to the ANOVA, the grain yields of wheat cultivars were significantly different ($p<0.001$), and significant differences between the sowing times ($p<0.001$) were found. However, there were no significant differences in interactions between cultivars (CV) x sowing time (ST) ($p=0.168$) (Table 56).

Table 56: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Rauischholzhausen 2016.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	17.3	17.28	1	2.6975	0.242
Cultivars (CV)	4648.3	516.47	9	80.6246	<0.001
Sowing time (ST)	96.1	96.14	1	15	<0.001
CV × ST	86.6	9.64	9	1.5047	0.168

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

The average yield of the cultivars ranged from 67.8 dt/ha for PZO Pilgrim to 95.8 dt/ha for KWS Ferrum (Figure 41).

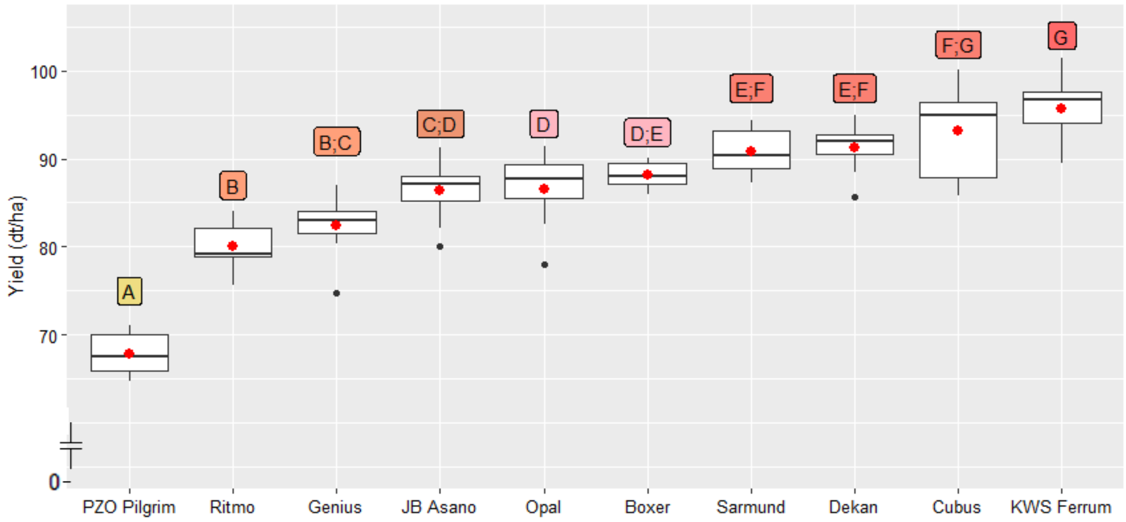

Figure 41: Yield comparison (dt/ha) of the wheat cultivars *p*-value CV (*p*<0.001), Rauischholzhausen 2016. The lines show the scattering range and the black point indicates the out-layer.

The delayed sowing time increased the grain yield of cultivars significantly about 2 dt/ha. The scattering was similar at both sowing times (Figure 40).

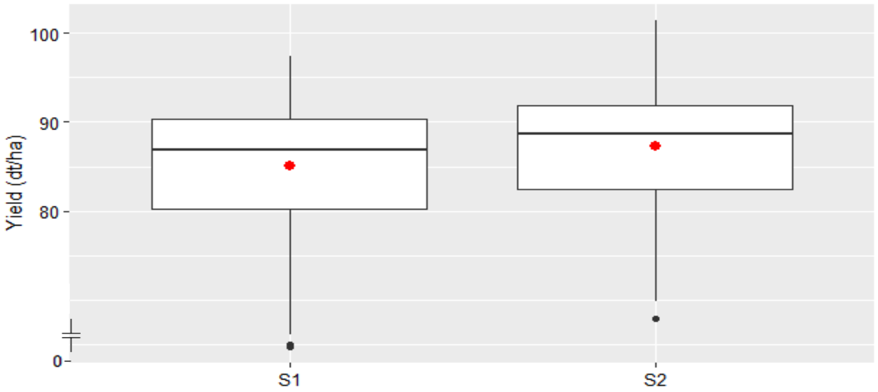

Figure 40: Yield comparison (dt/ha) of the wheat cultivars, *p*-value ST (*p*<0.001), Rauischholzhausen 2016. The lines show the scattering range and the black point indicates the out-layer, S1 early, S2 late sowing time.

4.3.2 Year 2017

The data set of the ANOVA in 2017 included ten line-cultivars in combination with two sowing times, and three replications. According to the ANOVA, there were significant interactions between cultivars x sowing time (*p*<0.001), also the grain yields of cultivars in Rauischholzhausen were significantly different (*p*<0.001). However, there were no significant differences between the sowing times found (*p*=0.085) (Table 57).

Table 57: Two-way ANOVA of the grain yields depending on cultivars and sowing times, Rauischholzhausen 2017.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	21.82	21.82	1	6.144	0.244
Cultivars (CV)	1649.34	183.26	9	51.6025	<0.001
Sowing time (ST)	11.09	11.094	1	3.1239	0.085
CV × ST	336.92	37.436	9	10.5412	<0.001

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

The Post-hoc analysis showed that except KWS Ferrum, the differences in grain yield between the sowing times were not significant (Figure 42). KWS Ferrum had a mean yield of 83.8 dt/ha in the first sowing time and 70.6 dt/ha in the second. The cultivars Cubus, Sarmund, and Dekan also had a higher grain yield in the first sowing time. The grain yield was higher for PZO Pilgrim, JB Asano, and Boxer in the second sowing time, but there were no significant differences compared to the first sowing time. Grain yield differences between the first and second sowing times were less than 0.5 dt/ha for Genius, Ritmo, and Opal. Sarmund reached the highest grain yield (S1: 88.3 dt/ha / S2: 87.1 dt/ha), followed by Boxer (S1: 84.1 dt/ha / S2: 86.1 dt/ha) and JB Asano (S1: 82.6 dt/ha / S2: 86.2 dt/ha). Furthermore, PZO Pilgrim had the lowest grain yield (S1: 65.6 dt/ha / S2: 70.8 dt/ha).

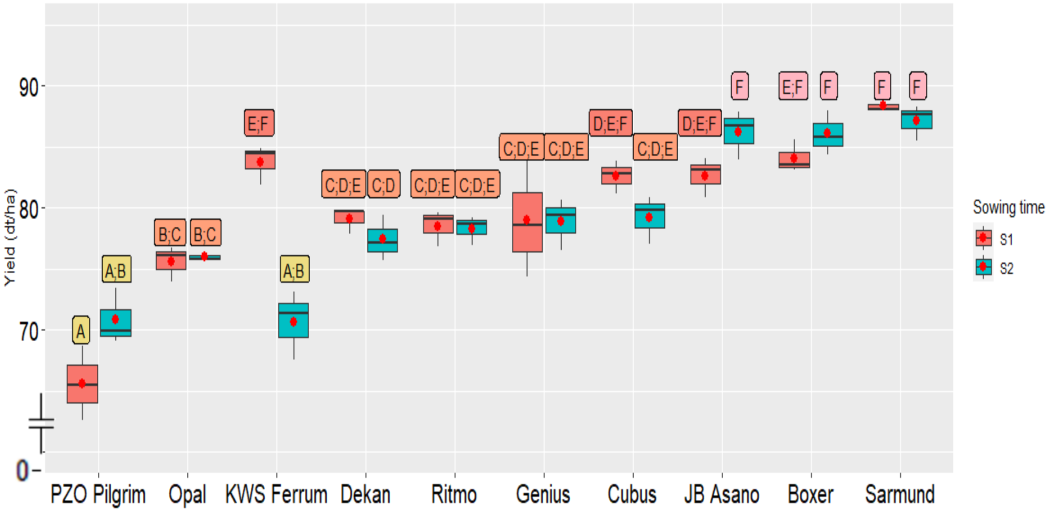

Figure 42: Yield comparison (dt/ha) of the wheat cultivars in different sowing time, *p*-value CV x ST (*p*<0.001), Rauischholzhausen 2017. The lines show the scattering range and the black point indicates the out-layer. S1 early, S2 late sowing time.

4.3.3 Year 2018

The data set of the ANOVA in 2018 included eight cultivars (four hybrids and four lines), each with four replications and within the same sowing time, as no sowing time delay was carried out (one-factor experiment). According to the ANOVA, the grain yields of wheat cultivars in Rauischholzhausen in 2018 was significantly different (*p*<0.001) (Table 58).

Table 58: ANOVA of grain yield depending on cultivars and sowing times, Rauischholzhausen 2018.

Source of variation	SS	MS	DF	F value	*p*-value
Replication	1.96	1.958	1	0.4722	0.5
Cultivars (CV)	1559.7	222.815	7	53.7291	<0.001

Notes: SS: sum of squares due to the source, MS: mean of sum of squares due to the source, DF: degrees of freedom in the source.

With 109.4 dt/ha Lear had the highest mean grain yield in 2018. The yield of Lear varied significantly from the yield of other cultivars, except for Hybery (106.0 dt/ha). In comparison to hybrids, all lines except Lear had lower grain yield (Figure 43).

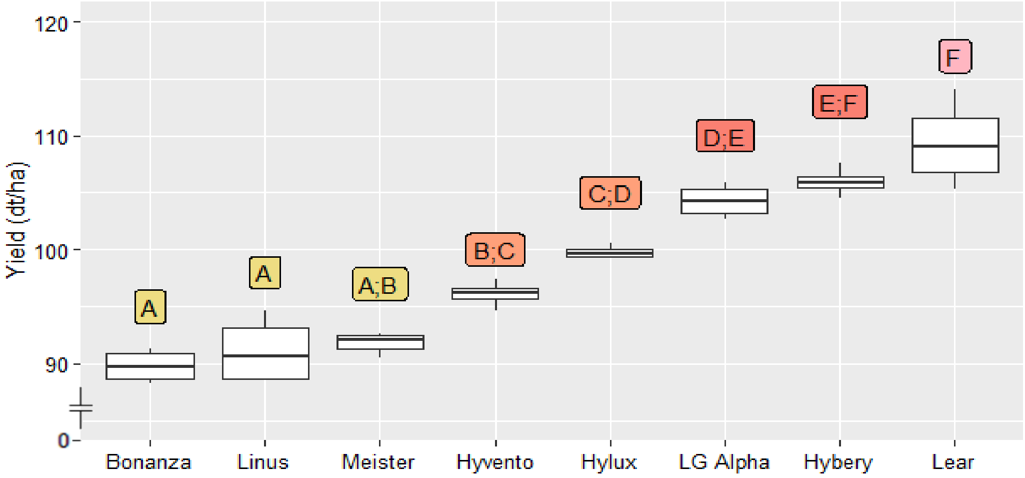

Figure 43: Grain yield comparison (dt/ha) of the wheat cultivars *p*-value$_{(CV)}$ <0.001, Rauischholzhausen 2018. The lines show the scattering range and the black point indicates the out-layer.

A two-sample t-Test revealed a difference in grain yield between line and hybrid cultivars (*p*=0.017). The grain yield difference between hybrid and line cultivars was 6 dt/ha (Figure 44).

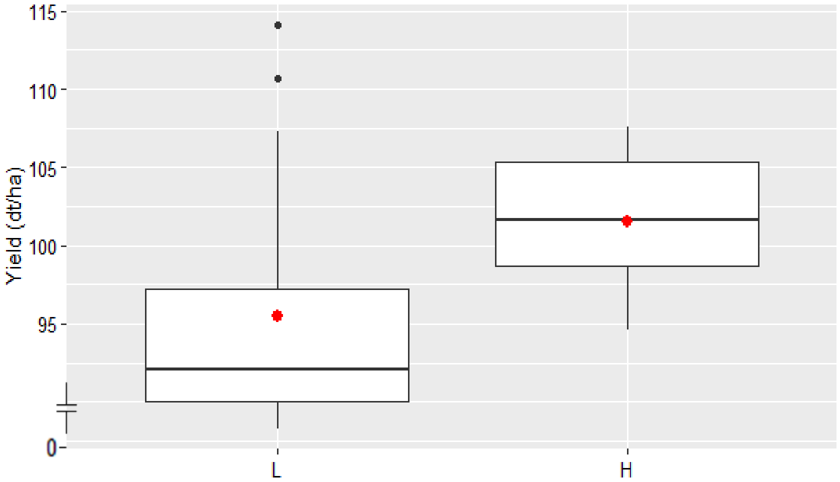

Figure 44: Yield comparison (dt/ha) of the wheat cultivars 4 hybrid (H) and 4 line (L), *p*-value CV (*p* <0.001), Rauischholzhausen 2018. The lines show the scattering range and the black point.

4.4 Yield stability of hybrids and line cultivars

Over the years, the shifting cultivars in the study made it difficult to find a suitable subset of the data. Therefore, the data from 2012 to 2014, three lines (Linus, Lear, Meister) and three hybrids (Hystar, Hybred, Hybery) were chosen in combination with two sowing times and two locations (Giessen, Gross Gerau). According to Wricke's ecovalence method, the lower ecovalence value leads to the higher the yield stability. Hystar had the lowest yield stability, while Linus was the cultivar with the highest yield stability (Figure 45).

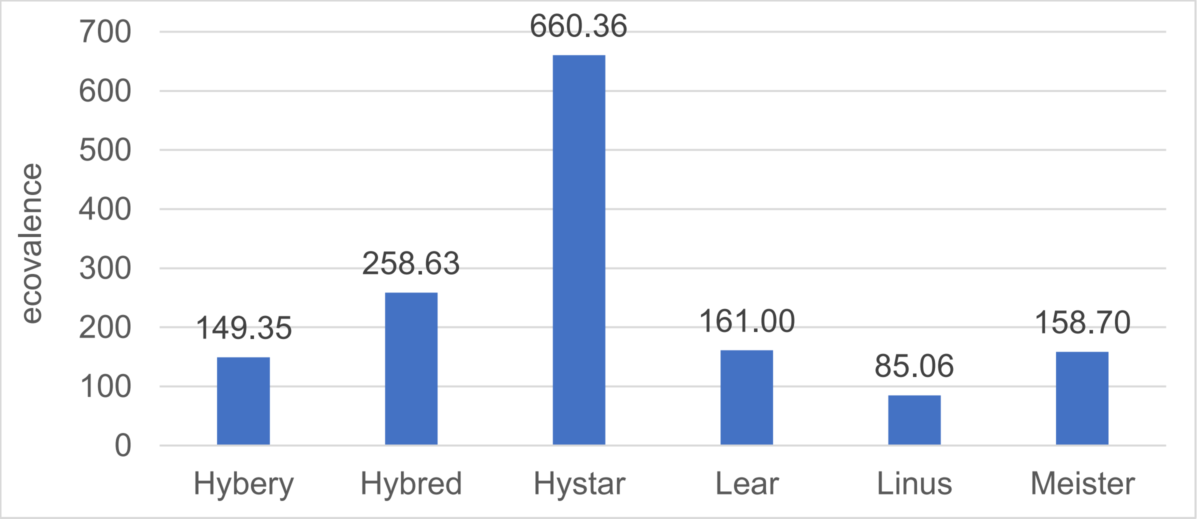

Figure 45: Wricke’s ecovalence value for six cultivars in two environments (GI and GG). Hybery, Hybred and Hystar are hybrid cultivars and Lear, Linus and Meister are line cultivars.

Another stability analysis performed on the yield data was the Eberhart and Russel approach. The sum of squares for cultivars (S2di) of this analysis states that the lower the S2di, the more stable the yield. Based on S^2di estimates, the yield stability of cultivars ranked as follows: (1) Linus (5.2), (2) Lear (12.5), (3) Hybery (13.5), (4) Meister (16.0), (5) Hybred (25.2), and (6) Hystar (57.4). Further insights into the yield behavior of the investigated varieties should be provided by the regression analysis.

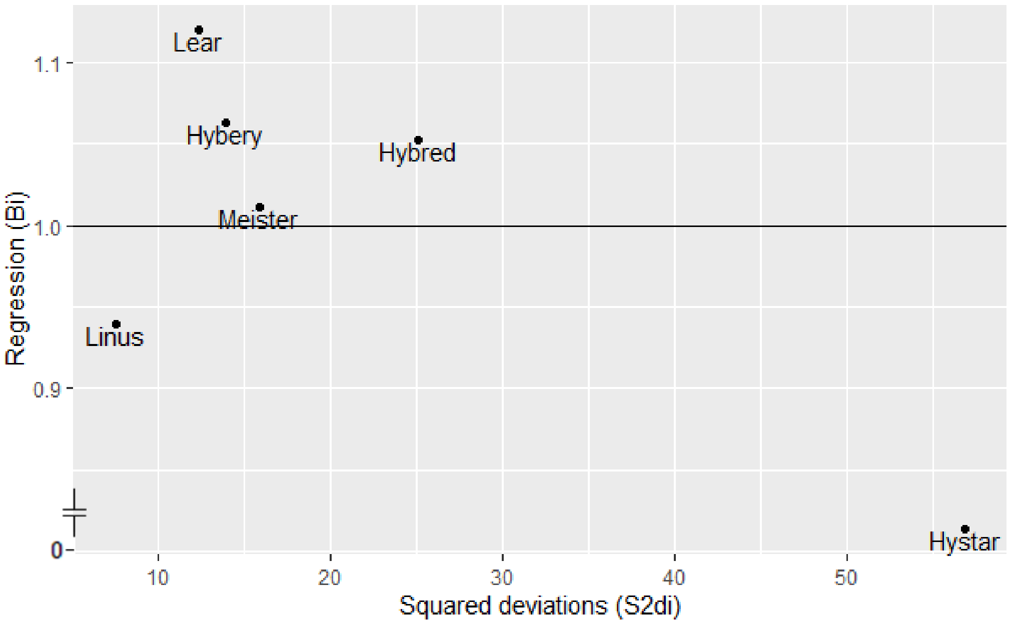

Figure 46: Sum of squares values belongs for variety i (s^2di) and Bi regression coefficient values of variety i (Eberhart and Russell, 1966). Hybery, Hybred and Hystar were the hybrid cultivars and Lear, Linus and Meister were the line cultivars.

The regression coefficient of cultivars (Bi) estimated approach specifies whether the cultivar is better adapted to high yielding conditions (Bi >1.0) or poor yielding conditions (Bi<1.0). Bi estimates show that cv. Lear, Hybery, and Hybred adapted better to high yielding environments (Bi >1.0), while cv. Linus and Hystar adapted better to poor yielding environments (Bi <1.0). cv. Meister prefers neither poor nor high yielding conditions (Bi=1) (Figure 46).

In Figure 47, the environmental index (EI) was plotted against the predicted yield. Thus, the environment index indicates whether the environment yielded a lower (minus) or greater (plus) yield. Cv Hybery had a high yield in all conditions, while cv Hystar had the best yield in the environment with the lowest yield.

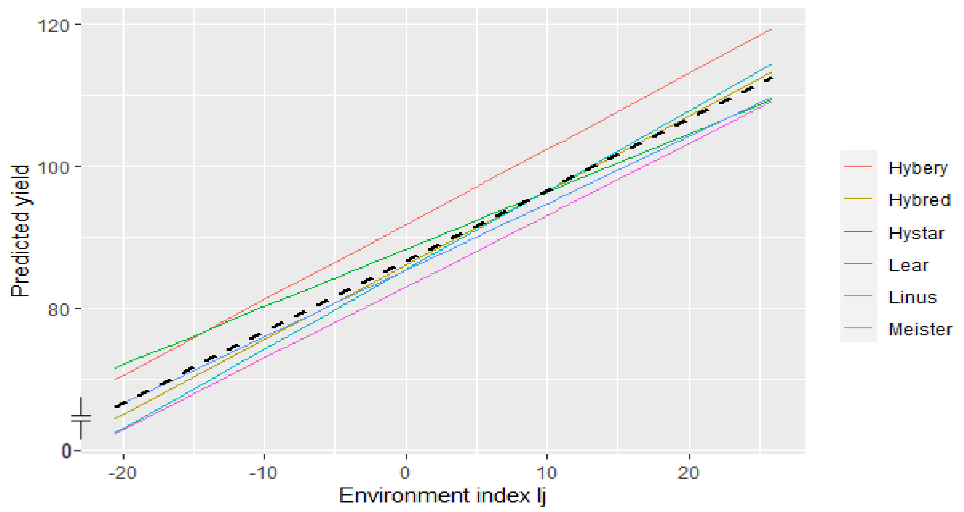

Figure 47: Environment index values (Ij) in relation with predicted yield (Eberhart and Russell, 1966) in wheat cultivars. Hybery, Hybred and Hystar were the hybrid cultivars and Lear, Linus and Meister were the line cultivars.

The EI of the different locations listed in Table 59 show that Gross Gerau had a lower yielding environment in 2012 and 2014 but had a greater yielding environment in 2013 at both sowing times. In comparison to other years, Giessen 2012 had the lowest yielding environment at both sowing times.

Table 59: Environment index based on Eberhart and Russell method. GG= Gross Gerau, GI= Giessen, sorted by the environment index, from lowest to highest.

Locations	Year	Sowing time	Environment Index (EI)
GG	2012	S1	-20.6
GG	2014	S2	-19.8
GG	2014	S1	-15.7
GG	2012	S2	-10.1
GI	2012	S1	-6.6
GI	2012	S2	-5.2
GG	2013	S2	3.3
GG	2013	S1	6.3
GI	2013	S2	10.6
GI	2013	S1	10.7
GI	2014	S2	21
GI	2014	S1	25.9

5 Discussion

5.1 Grain yield performance of wheat hybrids compared to line cultivars

Due to the lack of and indeed the existence of contradictory information about the yield performance and stability of hybrids and line cultivars in wheat, this study was conducted to determine the factors extent to which wheat hybrids are superior in grain yield and yield stability compared to line varieties. There have been few studies on physiology, yield components, and stability of wheat hybrids. Research on root development, response of each variety under different environmental conditions, optimal seed density, and experimental locations are all needed in this regard. Furthermore, for each study, the combination of management, climate, and genetics, as well as their interactions, should be considered.

Some studies in wheat have shown that hybrids surpass line cultivars in yield performance. Thus, in an US study, a long-term experiment (1975-1995) assessed the trend and stability of wheat hybrid and line cultivars in four different locations. As a result, hybrid wheat in the southern Great Plains of the United States was found to deliver an enhanced grain yield (approximately 11%) but no stability advantage over line cultivars (Koemel et al., 2004). Also, in an investigation of a large number of 119–132 wheat cultivars in Germany no significant differences in yield stability performance between hybrid and line cultivars were found (Liu et al., 2017).

In another US study, when wheat hybrid and line cultivars were compared in advanced experiments, the hybrid advantage against line was 0.65 t/ha, with an average yield level of 4.83 t/ha. This amounted to a 13.50 % average hybrid advantage over four years of regional testing (Bruns and Peterson, 1998). The present study, conducted at three German experimental locations (Giessen, Gross-Gerau, and Rauischholzhausen) confirms previous research findings on the advantages of wheat hybrid yield over the line cultivars (Liu et al. 2017; Koemel et al., 2004; Bruns and Peterson, 1998).

Grain yield comparisons hybrids vs. line cultivars in Giessen and Rauischholzhausen

Between 2012 and 2019, there was a significant positive correlation in grain yield (r=0.945***) between line and hybrid cultivars in Giessen. Neither hybrid yields nor line yields correlated with yield differences between hybrids and lines (Table 27). In other words, grain yields of hybrid and line cultivar changes in Giessen followed a similar pattern.

In six of eight experimental years in Giessen from 2012 to 2019, hybrid cultivars outperformed line cultivars. The average production of hybrids and lines was 94.60 (dt/ha) and 88.66 (dt/ha), respectively resulting in a relative grain yield difference of 8% increase in hybrid productivity compared to wheat lines. The cultivars reacted similarly in Giessen and Rauischholzhausen with an increase of the hybrid yield over the lines (Giessen 8%, Rauischholzhausen 6%). This value is clear evidence of the heterosis effect and the superiority of hybrids. The value is comparable to the results of other authors (Liu et al., 2017; Mühleisen et al., 2014; Koemel et al., 2004).

On the other hand, the heterosis effect found here is lower than for hybrids in cross-pollinators such as rye (Ismagilov et al., 2022; Haffke et al. 2015), rapeseed (Wang et al., 2020), and maize (Duvick, 1997). Furthermore, the additional yield must also be evaluated economically. Especially with regard to the additional costs of the hybrid seed, a yield superiority of 6 % might not be sufficient (Longin et al., 2012; Akel et al., 2019).

However, in Giessen 2014 and 2017 the grain yield of hybrid and line cultivars was equal (2014: lines 110 dt/ha, hybrids 110.5 dt/ha; 2017: lines 78.9 dt/ha, hybrids 78.8 dt/ha). Looking at the climatic conditions, it can be seen that the precipitation in both years 2014 and 2017 was above average (449 and 474 mm respectively), which caused a later harvest date. In contrast to 2017, there was a high level of global radiation of 928,396 kWh/m^2 in 2014. It is therefore assumed that the combination of high radiation and precipitation led to particularly high grain yields in 2014. While in 2017 there was indeed high precipitation, but accompanied by, less global radiation (Table A 10), with the result that grain yield was lower than in 2014. High amount of precipitation and high amount of global radiation lower the yield difference between hybrid and lines. This result means that under favourable growing conditions (rainfall, global radiation) and in the absence of abiotic stress, the yield superiority of the hybrids was reduced. Conversely, this finding could also be interpreted to mean that the hybrids are more likely to be superior in yield to line varieties under stress conditions.

The availability of reports, which demonstrated that the decrease in solar radiation caused decreased yield performances in crops such as wheat (Jia et al., 2021; Mu et al., 2010) and maize (Yang et al., 2022) could confirm the reaction of plants to the global radiation. However, up to now, no study has focused on the difference of the reaction to global radiation between wheat hybrids and line cultivars.

The correlation between precipitation and yield differences between hybrids and lines was significant negative (r=-0.578*) (Table 32). This means that the higher the precipitation was, the higher the grain yields of lines became in relation to the grain yield of hybrids. In other words, hybrids could show their yield advantage under drier conditions with good soil quality (silty clay texture) as was the case in Giessen. The early maturity of the wheat in the other years results from a low availability of water, which the hybrids tolerated better than the lines. Other research proves the result of this study that hybrid wheat also outperforms inbred lines in sturdiness to abiotic and biotic stress. For example, Mette et al. (2015) reported hybrids compared with lines showed higher yield performance due to less stress sensibility. It is assumed that the improved agronomic traits of the hybrids result from complementary selection of inbred traits leading to improved heat tolerance in hybrids (Bruns and Peterson, 1998).

The differences in grain yield performances between hybrid and line cultivars could also be explained by a difference in root growth. In previous studies in wheat, hybrids showed different genes and gene expressions compared to lines associated with increased root growth (Wang et al., 2006; Yao et al., 2005; Song et al., 2007). Fang et al. (2017) reported that lines with a higher subsoil root growth showed higher grain yield in water stress environment, than lines with a higher topsoil root growth. He also reported that the cultivars change their water consumption in a different way through the growing period. That means depending on the time in the growing season, where the individual cultivar has the highest water uptake, and the interaction with the water availability in the same point, has high influence in grain yield (Farooq et al., 2014; Luche et al., 2015; Christopher et al., 2016). Fang et al. (2017) reported that one wheat cultivar needs less soil water in elongation than other cultivars, but more in time between stem elongation and anthesis. Therefore, depending on when in the growing season the water availability was higher, wheat cultivars profited in different ways. Arai-Sanoh et al. (2014) reported similar results in rice.

In this study the focus was on comparing yield performance and yield stability of wheat hybrids and inbred lines. An important parameter influencing the yield level and stability of wheat is the infection (resistance) by fungal and viral diseases. Unfortunately, no data are available on the different reactions of hybrids and lines against diseases that are prevalent in wheat (*Puccinia sp.*, *Septoria nodorum*, *Septoria tritici*, *Fusarium graminearum*). However, from the results of other studies, it appears that the epidemiological expression in hybrids compared to lines could also be the reason for the higher yield performance in hybrids (Kalous et al., 2015; Longin et al., 2013; Martin et al., 2013; Eberhard et al., 2010; Schmid et al., 1994).

Due to the similarity in environmental conditions in Giessen and Rauischholzhausen, the same performance of hybrids and line cultivars in both trials (Giessen and Rauischholzhausen) was expected. In Rauischholzhausen, hybrids and lines were compared only in 2018, and the hybrids showed a higher grain yield (101.50 dt/ha) than the lines (95.50 dt/ha), resulting in a 6.28 % increase in yield.

Gross Gerau

In Gross Gerau, hybrids outperformed lines in four of the eight measured years between 2012 and 2019. Overall, hybrid and line average yields were 72.14 (dt/ha) and 70.85 (dt/ha), respectively, resulting in a 1.82% increase in hybrid productivity over the lines. However, there was an interaction with the years, because in some years the grain yield superiority of the hybrids was clear and in other years it was not. Therefore, it cannot be ruled out that the yield superiority of hybrids can only be achieved if the growing conditions and agronomic measures are adapted accordingly. Similar effects occurred with barley. For example, Mühleisen et al. (2014) demonstrated that hybrid cultivars of barley had higher potential yield than lines on average, but individual high-yielding lines may compete with and even outperform the best hybrids.

Also, in our own study with wheat cultivars, carried out from 2012 to 2019, the line cultivars Linus, Lear, Meister, Bonanza, and Egoist were among the top three most productive cultivars in either Giessen or Gross Gerau. For this reason, based on the study conducted, it can be concluded that high-yield lines can compete with and even exceed high-yield hybrids.

The reduced performance of hybrids compared to line cultivars in Gross Gerau (1.82 %), compared with the other two trials (GI and RH) could explained as followed:

(1) The recommended seed density of hybrid wheat is 120-140 grains/m² (Saaten-union 2022). But in this study due to having better comparability between lines and hybrids, the seed density in both hybrids and lines was in a range of about 250-350 grains/m² (taking into account the specific and local conditions). This should prevent a seed density effect from being included in the yield determination; however, this may have had a negative effect, which meant that the yield potential of hybrids could not be exhausted due to low water availability. Thus, it is presumed that the yield gap could be caused by high seed density in combination with poor water availability or water holding capacity of the soil type (Cooper et al., 2021). Another study carried out with maize reported that the development of hybrids in maize is feasible once concurrent selection for high plant yield and stability is applied at very low plant densities. In this study, hybrids improved concurrently for high plant yield and stability of performance had significantly higher yield than the control hybrid B73Mo17 at three different densities (0.74, 2.5, and 4.2 plants/m^2), while maintaining the same productivity at the high plant density of 8.4 plants/m2 (Tokatlidis et al., 2011). The results from the studies with maize are not one-to-one transferable to wheat, however, as the data available so far on seed density differences in hybrids and lines are poor.

(2) Due to the unfavourable soil characteristics of Gross Gerau (water stress and sandy soil) in comparison to Giessen and Rauischholzhausen, lower grain yield in both hybrids and lines were observed. However, the yield of lines was influenced less, while the yield of hybrids was affected more, resulting in a yield differential of only 1.8% between hybrids and lines. Similar effects occurred with triticale in the findings of Mühleisen et al. (2014) who demonstrated that drought stress increased field heterogeneity in wheat hybrids, which leads to lower heritability and lower grain yield. It presupposed that hybrid wheat has different

requirements for growing conditions than line varieties. Hybrids for high performance need optimal situations, which means that under favourable conditions they will reach a high level of yield and even stability (Evan et al., 1999). Gross Gerau is a low-yield location with sandy soil, the water passes fast from the upper 30 cm into deeper layers, especially through the channels made by roots and earthworms. Nevertheless, the nitrogen cycles need water to transform the ammonium nitrogen to nitrate, which is taken up by the plants. The bacteria designated as complete ammonia oxidizers oxidise the ammonium that is positive charged to the negatively charged nitrate, which leached as the water flows through (Wolkowski et al., 1995). The low water capacity and the lower availability of nitrate in the soil may have contributed to the deviating result in Gross Gerau.

(3) It was also found that in a drought-stressed environment, such in Gross Gerau, weather conditions significantly affected hybrid and line yield performance. The climate parameter NOD <0 °C air temperature was identified as key contributor to yield discrepancies between hybrid and line cultivars. In Gross Gerau, the years 2012 (19 days), 2013 (40 days), and 2017 (32 days) had colder temperatures (<0°C) than other years. As a result, in these years hybrids yielded significantly more than line cultivars. This suggests that hybrids are more likely than line cultivars to be resistant to cold stress, however the different reaction of hybrids and lines to the cold temperature in winter is not necessarily related to cold resistance (less plant loss) but can also be related to the different cycle and stages of development that the plants reach before the onset of winter. For example, mild winters promote further differentiation of the apex or the establishment of more side shoots/tillers (Tian et al., 2022), whereas cold winters stop this development. It could be that the varieties benefit or are inhibited differently from a greater number of tillers (Peng et al., 2021). Another solution to rescue from freezing, is increasing the amount of carbohydrate due to more physiological activities of plants, such as photosynthesis (Tian et al., 2022), increased amount of photosynthesis could rescue the plant against the freezing and enhance the grain yield as well which could be the reason for superiority of hybrids compare with lines.

(4) In Gross Gerau the precipitation sums from January to harvest time significantly correlated with the grain yield of line cultivars (r=0.526*), but not for hybrids (Table 52). This indicates that the more precipitation, the higher the yield in line cultivars, and vice versa. Or, this finding can also be interpreted to mean that hybrids react less clearly to good water supply and tend to be more drought tolerant. However, there was one exception to this conclusion. Compared to other years, 2015 had the least amount of rain (235 mm) from January until harvest time. Even though 2015 was a drought year, line yields were equivalent to hybrid yields.

(5) One reason for the lower yield differences in Gross Gerau could be the root formation of the wheat. There are many contrasting studies on the value of the root system under drought stress for grain yield. For example, some researchers show that wheat cultivars with large extended root system have high superiority in water stress (drought) environment to absorb more soil water and relief drought stress (Palta et al., 2011; Ehdaie et al., 2012). However, other researchers show as long as the roots are a major sink for nutrition and water, extended root system caused reduce yield performance in wheat cultivars (Siddique et al., 1990; Zhang et al., 1999; Song et al., 2009), which means that a small root system could have a positive effect on grain yield in water-limited situations (Passioura, 1983, Zhu and Zhang, 2013). Genotypes with an extended root system, especially in topsoil where the availability of water and nutrition is more should be able to capture soil moisture from the topsoil during occasional spring rainfall and use it for grain filling (Manske and Vlek, 2002; Palta et al., 2011; Ehdaie et al., 2012). These studies support the hypothesis that hybrids, due to high root growth, have an advantage over lines in soils with a good water holding capacity due to increased root formation (Giessen, Rauischholzhausen), but a larger root system in a dry soil, as in Gross Gerau, has no advantage.

(6) Drought tolerance is associated with morphological and physiological characteristics such as plant architecture (Hyles et al., 2020), leaf area, cuticular resistance and thickness, stomata size and density (Aruna et al., 2019), transpiration (Sarto et al., 2017) and hormonal regulation (Burges et al., 2016). Whether the named characteristics really differs between wheat hybrid and line cultivars, cannot be said yet. However, further research can be done to show the morphological and physical differences between the cultivar types.

Another aspect was investigated by Duvick et al. (2004) who supposed that the environment could actively affect the grade of heterosis. This was found in maize where hybrids usually show more heterosis in stressful than non-stressful environments, even as overall performance is decreased (Duvick et al., 2004). The lack of consistent levels of heterosis across traits may prove that heterosis could not be explained in this study due to the stress condition in Gross-Gerau.

(7) From a genetic viewpoint, heterosis in multiplicative complex traits is explained without a biological dominance (Cros et al., 2015; Dan et al., 2015; Fiévet et al., 2018). Even when component traits diverge phenotypically in parents, the competent traits remain near the mid-parent. For example, the hybrid advantage against line in wheat was 0.65 t/ha (Bruns and Peterson, 1998). The same result is reported in commercial maize, because of the longer hybrid breeding cycle, lines approach hybrid performance (Troyer and Wellin, 2009). However, the results which were mentioned in maize are not directly comparable with wheat, but gives a hint that heterosis does not always have to occur.

5.2 Grain yield stability of wheat hybrids and lines

There is a lot of conflicting information about the yield performance and yield stability of hybrids compared to lines. Many studies mentioned that the hybrids recorded higher yield stability compared to the lines. For example, a German study Mühleisen et al. (2014) compared the yield stability of hybrids to lines in three cereals, wheat (1606 hybrids and 143 lines), barley and triticale, in five locations. They showed in wheat and barley the hybrid varieties were significantly ($p < 0.05$) more stable than lines. The result of their study is also supported by (Longin et al., 2013; Gowda et al., 2010; Corbellini et al., 2002; Oury et al., 2000).

In contrast, several studies found that in wheat the hybrids exhibited no benefit in yield stability compared to lines (Koemel et al., 2004; Bruns and Peterson, 1998; Peterson et al.,1997; Perenzin and Borghi, 1988). In one German study which was run by Liu et al. (2017) no difference in yield stability performance between hybrids and lines ($p > 0.20$) was reported. Furthermore, under different environmental conditions (considering 50 locations) no significant differences have been found on yield performance of hybrids and lines among 132 wheat genotypes (Reif et al., 2017). Also, in triticale a very weak yield stability has been found among hybrid and line varieties. To some extend hybrids even presented a lower dynamic in yield stability than of lines (Mühleisen et al., 2014). Comparing 940 wheat genotypes including hybrid and line varieties in France during 2010 and 2011, weak yield stability has been observed in hybrid varieties (Gowda et al., 2012). In other study in Germany, no advantage in hybrid rye varieties has been observed compared to lines (Haffke et al., 2015).

The most important aspect regarding yield stability is the reproducibility of the data. Several studies explained although in wheat the hybrids had higher yield performance but not reproducibly expressed by the data (Mühleisen et al., 2014; Sneller et al., 1997; Jallaludin et al., 1993; Pham et al., 1988; Becker et al., 1988).

Mühleisen et al. (2014) showed that the repeatability of the data in the wheat experiment from 2010-2011 between five locations was low (SDM=0.41- 0.58). However, this amount was higher for barley (SDM=0.77- 0.91) and triticale (SDM=0.72- 0.92). The repeatability of data in triticale experiment was higher than barley and wheat but the average of heterosis by the individual environments ranged between -4.6% and 7.2%.

The studies showed that heritability can be increased when the number of test environments is increased (Mühleisen et al., 2014), which could be the reason for different results reported in both German studies (Mühleisen et al., 2014 and Liu et al., 2017). The total number of environments in the experiment carried out by Liu et al. (2017) was about up to 50 locations. In studies by Mühleisen et al. (2014), however, this number was only about 20. In fact, for the analysis of yield stability, number of 50 to 200 environment would be considered (Piepho, 1998). In addition, the number of 40 environments was used to calculate the yield stability between hybrid and line varieties recommended by Reif et al. (2017). In contrast, Becker (1988) explained, at least 10-15 environments should be considered for the yield stability calculation, when the limited environmental conditions often provide underestimation or overestimation of genotype traits.

Another reason which influenced the yield stability of the cultivars could be the intensive selection during the breeding processes which led to a limitation of the diversity of yield stability performance. Thus, it is assumed the limited number of hybrids and the small number of locations for stability evaluation could be the main reason for different results between our own research and the aforementioned studies (Liu et al., 2017 and Mühleisen et al., 2014). Peng et al. (1999) showed that the yield of a current rice variety was lower than when it was first released 30 years ago. They concluded that the main reason for the lower yield was line plant selection at all stages of the breeding program.

The increase of the heterogeneity could be another reason for reduced superiority of hybrids compared with lines. Mühleisen et al. (2014) came to this conclusion in studies they conducted with triticale. They explained in the breeding process, the male parents should be selected from several females and not just one individual. Wilson and Driscoll (1983) reported the recovery on the genetic background of female parents in hybrid wheat as well. The negative effects of the cytoplasmic male sterility merging as heterosis effects in hybrid wheat cultivars could be another reason for poor grain yield performance in hybrid varieties in comparison with lines (Mühleisen et al., 2014). The negative effects of the cytoplasmic male sterility on rice grain yield have been observed (Qin et al., 2013).

The activities and expressing of the individual gene in the hybrids could be another factor influencing yield stability of wheat. It has been shown that when three functionally similar genomes, which are diverse, come together it causes differential gene expression among several other outcomes (Sharma, 2013). It means in breeding process even if all genes which are responsible for better performance come together, it could possible that hybrid do not perform heterosis compared with parents due to negative midparent heterosis (Boeven et al., 2020; Oakley et al., 2015; Lynch and Walsh, 1998; Waser and Price, 1994).

Furthermore, in fact, the heterosis is the result of the environment x cultivation system (Tollenaar et al., 2002). There are many studies available which reported that the genotypes could be influenced considerably by environmental conditions (Tokatlidis et al., 2001; Tokatlidis et al., 2006; Tokatlidis et al., 2011; Fasoulas, and Fasoula, (1995) and the interaction of genotype × environment × management has a high influence on the yield stability (Cooper et al., 2021; Ray et al., 2015).

The present study estimated the dynamic stability of three hybrid cultivars (Hybery, Hybred, Hystar) versus three lines (Leer, Linus, Meister) from 2012 to 2014. The dynamic stability assessed using two approaches: (1) Wricke's (1962) (Wi2) ecovalence, and (2) Eberhart and

Russell's (1966) slope value (bi), environmental index (EI) and variance of regression deviations (S^2di). Both approaches showed almost the same ranking for the stability of cultivars.
Between the line cultivars, Linus was the most yield-stable, whereas the hybrid variety of Hystar was the least yield-stable in both approaches. The remaining four cultivars had moderate yield stability, as shown in Figure 45 and Figure 46. Although Hystar had the lowest yield stability than others but showed the highest yield in Gross Gerau during years 2013-2015. This variety could be a promising choice in lower-yield environments like Gross Gerau as supported by the environmental index analysis. In addition, the yield of Linus ranked sixth out of nine in annual comparisons of Giessen and Gross Gerau despite having the highest stability (data not shown). Otherwise, while Linus has a high level of stability, it does not produce as much as high-yielding hybrid cultivars.

Measurements of yield stability in broader contexts, as well as using a different collection of cultivars for trials, may have resulted in differing results of yield stability (Liu et al., 2017; Mühleisen et al., 2014). Other factors, such as differences in precipitation, air temperature, diseases, weeds, soil fertility and structure, and agricultural management, can affect the crop yield throughout the years (Seufert and Ramankutty, 2012). Furthermore, according to a study by Macholdt and Honermeier (2019) based on a long-term field experiment in Germany, the level of N fertilization, followed by annual weather conditions and different crop rotation methods, might affect yield stability differences (Macholdt and Honermeier, 2019). In the present study, over the years, the shifting cultivars in the study made it difficult to find a suitable subset of the data. As a result, the yield stability analysis was limited to three years and over six cultivars. Therefore, in the context of a long-term study, the stability analysis must be confirmed in more locations and over a longer period.

5.3 Effect of delayed sowing on the grain yield reaction of hybrids and lines

The current study found that delayed sowing had moderate (no significant) correlation on hybrid and line yield differences in Giessen (r=0.594) but had a very close (significant) correlation in Gross Gerau (r=0.972***). The first sowing time in both locations was between end of September up to middle of October and second sowing time was about middle up to end of October. It supposed that due to the short time intervals between first and second sowing time on average (16 days) the second sowing time was not that much stressful for the cultivars used and they had enough time for growing and development and could compensate the disadvantages of late sowing time in Giessen with good environment. The results of this study are comparable with those of Koppensteiner et al. (2022) who reported, generally early sowing leads to early establishment of plants, which is a good strategy to rescue from environmental stresses. However, on sandy soil of Gross Gerau, due to abiotic stress caused by lower water and nutrient availability the cultivars could not compensate for the disadvantages of late sowing time. This statement is supported by studies from Poland and Austria which offer early sowing time, to reduce negative impacts of environment stresses such as heat and drought (Neugschwandtner et al., 2015; Jarecki and Bobrecka-Jamro, 2019).

It is assumed that due to better shoot formation in autumn, the beginning of apex development, stronger individual plants and nutrient uptake leading to better overwintering, the early sowing dates in cold climates are superior to the late sowing dates (Praveen et al. 2018; Anjum et al., 2021; Ding et al., 2016; Channa et al., 2016). On the other hand, mild winter periods may favor later sowing of wheat, as plant development can continue during mild winter periods.

Our findings reveal that in a low-yielding environment like Gross Gerau, the first sowing time led to higher grain yield than the second sowing time, with yield differences ranging from 0.35 to 16.33 dt/ha in hybrids and yield differences ranging from 1.4 to 13.81 dt/ha in lines (Table A.11). In Gross Gerau, delayed sowing led to higher grain yields than early sowing only in 2012 (in both hybrids and lines) and 2016 (in lines). Therefore, the present study strongly recommends early sowing to increase yield in a low-yielding environment like Gross Gerau.

The advantage of earlier sowing time than later sowing time can be explained by many reasons such as more shoots/tillers growth, development of the apex, enhancement of leaves per plant (Wang et al., 2006; Tilley et al., 2015), stronger individual plants, better root development and because plants have much more time to grow and adapt to stressful conditions with an early sowing time. It is reported that delaying sowing time significantly caused decrease in wheat the plant height, number of tillers, leaf area and root biomass (Koppensteiner et al.,2022; Ma et al., 2018).

Selecting a proper sowing time in high-yielding environments like Giessen is more complex than in low-yielding environments like Gross Gerau. The advantage of the first or second sowing time was not consistent in either hybrids or lines. In certain years, early sowing time produced more than late sowing time, while late sowing time produced more in others. Late sowing time produced more yield than early sowing time in the following years: in 2012 in either hybrids or lines, 2013 only in hybrids, 2015 only in hybrids, and 2016 in either hybrid or line cultivars. In the remaining situations, a contrasting pattern observed. Therefore, long-term data on sowing times are required to recommend a suitable sowing time in environments like Giessen.

Summary

In plant breeding, heterosis is now also used in self-pollinated wheat as an effective genetic strategy to increase yield and stress resistance. For the cultivation of wheat hybrids, not only their yield superiority over line cultivars is important, but also their response to different site, growth, and sowing conditions. However, there are few data on the yield performance of hybrid wheat compared to line cultivars under varying site conditions and delayed sowing.

Therefore, the main objectives of this study were (1) to characterize the effects of varying soil and growing conditions on grain yields of hybrid cultivars compared to line cultivars, (2) to determine yield stability among hybrid wheat compared to line cultivars, and (3) to clarify the response of hybrid wheat to sowing time delay compared to line cultivars.

The present study was conducted from 2012 to 2019 at three experimental sites in Gießen, Groß-Gerau and Rauischholzhausen, each of which had widely varying soil properties. A different number of wheat hybrids and line cultivars were considered in combination with one to two sowing time delays. The main or interaction effects of the two test factors (cultivars x sowing time delay) were investigated with an analysis of variance. The yield stability of the cultivars was determined with the help of the stability variance (according to Shukla), the eco-valence (according to Wricke) and the environmental index.

As a result of the investigations, a yield superiority of the hybrid cultivars over the line varieties of 8 % (Giessen site), 1.82 % (Groß-Gerau site) and 6.28 % (Rauischholzhausen site) was determined on average for the trial years. On soils with high water capacity, a clear and similar yield superiority of the hybrid wheat was thus achieved. On sandy soils, on the other hand, the yield differences between both cultivar types were significantly smaller.

The correlation between precipitation and yield differences of hybrids and lines was significantly negative. This means that the higher the precipitation, the higher the grain yields of the lines relative to the grain yields of the hybrids. It is therefore concluded that the hybrids were able to exploit their yield advantage under drier conditions with good soil quality (silty clay texture).

Among the line cultivars, Linus had the highest yield stability, although it only ranked 6th out of a total of nine cultivars in the yield ranking. In contrast, the hybrid cultivar Hystar had the lowest yield stability in both approaches. The remaining four cultivars had medium yield stability. Although Hystar had the lowest yield stability among the varieties, it achieved the highest grain yields and the best environmental index on the sandy soil in Groß-Gerau.

In Gießen, the two-week delay in sowing time had no significant effect on the yield differences between hybrids and line cultivars. In contrast, the sowing time delay in Groß-Gerau caused a

significant reduction in yield differences. It is concluded that the sowing delay of 16 days on average at the Gießen site was better compensated by the wheat than on the sandy soil in Groß-Gerau, where the water and nutrient supply was limited. Seeding time delays can therefore be better tolerated on a soil with high water capacity than on sandy soil. No interaction between sowing time delay and cultivar type (hybrid vs. line cultivars) was observed, so that hybrid wheat did not show a changed reaction to late sowing. On the other hand, the response of wheat to sowing time delay was not uniform among either the hybrids or the line cultivars. Therefore, reliable data on the growth behavior of wheat cultivars are needed to recommend a suitable sowing date depending on the site conditions (climate x soil).

Zusammenfassung

In der Pflanzenzüchtung wird Heterosis inzwischen auch bei selbstbefruchtendem Weizen als wirksame genetische Strategie zur Steigerung von Ertrag und Stressresistenz eingesetzt. Für den Anbau von Hybridweizen ist nicht nur ihre Ertragsüberlegenheit gegenüber Liniensorten wichtig, sondern auch ihre Reaktion auf unterschiedliche Standort-, Wachstums- und Aussaatbedingungen. Es gibt jedoch nur wenige Daten über die Ertragsleistung von Hybridweizen im Vergleich zu Liniensorten bei unterschiedlichen Standortbedingungen und verschiedenen Aussaatzeitpunkten.

Die Hauptziele dieser Studie waren daher (1) die Charakterisierung der Auswirkungen unterschiedlicher Boden- und Wachstumsbedingungen auf die Kornerträge von Hybridweizen im Vergleich zu Liniensorten, (2) die Bestimmung der Ertragsstabilität von Hybridweizen im Vergleich zu Liniensorten und (3) die Klärung der Reaktion von Hybridweizen auf eine spätere Aussaat im Vergleich zu Liniensorten.

Die vorliegende Studie wurde von 2012 bis 2019 an drei Versuchsstandorten in Gießen, Groß-Gerau und Rauischholzhausen durchgeführt, die jeweils sehr unterschiedliche Bodeneigenschaften aufwiesen. Es wurde eine unterschiedliche Anzahl von Weizenhybriden und Liniensorten in Kombination mit ein bis zwei späteren Aussaatzeitpunkten betrachtet. Die Haupt- bzw. Interaktionseffekte der beiden Versuchsfaktoren (Sorten x Aussaatzeitpunkt) wurden mit einer Varianzanalyse untersucht. Die Ertragsstabilität der Sorten wurde mit Hilfe der Stabilitätsvarianz (nach Shukla), der Ökovalenz (nach Wricke) und des Umweltindexes ermittelt.

Als Ergebnis der Untersuchungen wurde eine Ertragsüberlegenheit der Hybridsorten gegenüber den Liniensorten von 8 % (Standort Gießen), 1,82 % (Standort Groß-Gerau) und 6,28 % (Standort Rauischholzhausen) im Mittel der Versuchsjahre festgestellt. Auf Böden mit hoher Wasserkapazität (Giessen und Rauischholzhausen wurde eine ähnliche Ertragsüberlegenheit des Hybridweizens erreicht. Auf sandigen Böden (Groß-Gerau) hingegen waren die Ertragsunterschiede zwischen beiden Sorten deutlich geringer.

Die Korrelation zwischen Niederschlag und Ertragsunterschieden von Hybriden und Linien war signifikant negativ. Das bedeutet, dass die Kornerträge der Linien im Vergleich zu den Kornerträgen der Hybriden umso höher sind, je höher die Niederschläge sind. Daraus wird gefolgert, dass die Hybriden ihren Ertragsvorteil unter trockeneren Bedingungen mit guter Bodenqualität (schluffig-lehmige Textur) nutzen konnten.

Unter den Liniensorten wies Linus die höchste Ertragsstabilität auf, obwohl er in der Ertragsrangliste nur Platz sechs von insgesamt neun Sorten belegte. Dagegen wies die Hybridsorte Hystar in beiden Ansätzen die geringste Ertragsstabilität auf. Die übrigen vier

Sorten wiesen eine mittlere Ertragsstabilität auf. Obwohl Hystar die geringste Ertragsstabilität unter den Sorten aufwies, erzielte sie auf dem Sandboden in Groß-Gerau die höchsten Kornerträge und den besten Umweltindex.

In Gießen hatte der zwei Wochen spätere Aussaatzeitpunkt keinen signifikanten Einfluss auf die Ertragsunterschiede zwischen Hybriden und Liniensorten. Im Gegensatz dazu bewirkte die Verzögerung der Aussaat in Groß-Gerau eine signifikante Verringerung der Ertragsunterschiede. Daraus wird gefolgert, dass die Aussaatverzögerung von durchschnittlich 16 Tagen am Standort Gießen vom Weizen besser kompensiert wurde als auf den sandigen Böden in Groß-Gerau, wo die Wasser- und Nährstoffversorgung eingeschränkt war. Auf einem Boden mit hoher Wasserkapazität können spätere Aussaaten besser toleriert werden als auf Sandböden. Es wurde keine Wechselwirkung zwischen der späteren Aussaat und der Sorte (Hybrid- vs. Liniensorten) beobachtet, so dass Hybridweizen keine veränderte Reaktion auf die späte Aussaat zeigte. Andererseits war die Reaktion des Weizens auf die verspätete Aussaat weder bei den Hybriden noch bei den Liniensorten einheitlich. Daher sind zuverlässige Daten über das Wachstumsverhalten von Weizensorten erforderlich, um einen geeigneten Aussaattermin in Abhängigkeit von den Standortbedingungen (Klima x Boden) zu empfehlen.

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Appendix

Table A 1: Sum of air temperature > 0° C in Giessen 2011-2019

Cropping season	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Sum
2011/2012	294.2	135.2	150.4	107.8	71.3	251.0	273.1	472.5	477.4	561.0	2793.9
2012/2013	273.5	173.0	115.6	123.3	36.3	64.4	275.0	384.4	506.9	643.5	2595.9
2013/2014	344.8	158.6	123.3	120.3	137.8	231.4	357.6	411.0	507.9	631.8	3024.5
2014/2015	375.0	211.7	112.3	89.2	58.0	172.7	283.1	413.6	511.8	648.4	2875.8
2015/2016	287.6	224.8	211.9	100.7	123.0	152.7	261.5	448.3	533.3	610.7	2954.5
2016/2017	287.3	144.0	86.9	20.3	119.5	258.5	254.7	464.0	564.3	600.0	2799.5
2017/2018	357.6	164.5	117.9	152.5	13.8	139.5	393.4	530.7	567.6	672.1	3109.6
2018/2019	334.4	184.2	143.9	51.7	102.9	232.5	327.9	370.3	613.7	620.0	2981.5

Table A 2: Sum of precipitation (mm) in Giessen 2011-2019

Cropping season	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Sum
2011/2012	29.2	0.9	82.3	65.7	3.5	8.9	32.0	55.4	91.1	77.5	446.5
2012/2013	46.5	40.2	45.0	44.2	17.3	12.2	61.0	159.3	43.0	22.3	491.0
2013/2014	110.0	70.0	44.2	43.5	30.9	10.0	62.8	67.2	50.6	130.8	620.0
2014/2015	62.0	38.7	53.0	54.2	16.1	43.5	30.2	25.6	35.3	75.5	434.1
2015/2016	24.6	71.2	39.9	53.3	60.0	45.8	43.9	38.6	116.4	38.3	532.0
2016/2017	37.1	64.0	9.1	20.0	32.2	40.3	19.6	88.9	61.0	109.7	481.9
2017/2018	27.7	64.7	78.1	91.4	9.0	33.8	77.1	125.7	185.2	40.5	733.2
2018/2019	1.7	38.6	93	39.9	14.1	62.8	27.3	72.0	45.9	34.3	428.7
Long-term	49.0	57.0	63.0	49.0	40.0	44.0	41.0	58.0	62.0	66.0	529.0

Table A 3: Average of air temperature (°C) in Giessen 2011-2019

Cropping season	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Average
2011/2012	10.1	3.4	4.3	1.3	-0.9	7.9	6.8	15.4	11.9	17.9	7.8
2012/2013	8.2	4.2	4.1	2.5	0.6	1.0	6.9	13	12.7	20.7	7.4
2013/2014	9.5	3.8	3.5	3.9	5.0	7.5	11.9	13.3	16.9	20.4	9.6
2014/2015	12.1	4.3	3.5	2.7	1.9	5.6	9.4	13.3	17.1	20.9	9.1
2015/2016	9.3	7.5	6.9	2.5	4.2	4.9	8.7	14.5	17.8	19.7	9.6
2016/2017	9.3	4.5	2.1	-1.5	4.2	8.3	8.6	14.6	18.8	19.4	8.8
2017/2018	11.5	5.7	3.8	4.9	-0.9	3.9	12.8	17.1	18.9	21.7	9.9
2018/2019	10.8	6.1	4.6	1.7	3.7	7.5	10.9	11.9	20.5	20. 0	9.7
Long-term	9.0	4.3	1.6	0.3	0.8	4.4	8.4	12.9	16.0	17.8	7.5

Table A 4: Sum of air temperature > 0° C Gross Gerau 2011-2019

Cropping season	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Sum
2011/2012	334.3	169.3	179.0	138.4	82.9	283.4	312.2	521.2	527.6	608.5	3156.8
2012/2013	292.1	181.8	127.5	89.3	40.6	93.6	299.5	395.5	529.7	679.4	2729.0
2013/2014	357.6	169.4	124.0	132.7	146.0	259.6	397.5	441.4	556.0	652.0	3236.2
2014/2015	390.3	214.8	121.6	95.4	61.1	199.5	308.0	447.3	542.3	689.4	3069.7
2015/2016	298.8	240.8	209.1	120.9	136.3	172.6	280.8	458.9	541.7	639.0	3098.9
2016/2017	289.9	153.6	87.3	19.4	137.6	282.2	281.9	485.8	603.5	634.2	2975.4
2017/2018	361.5	172.8	119.5	182.3	21.8	159.3	425.5	551.9	619.1	712.1	3325.8
2018/2019	415.4	197.3	140.7	57.5	115.6	249.2	340.1	389.7	632.0	629.0	3166.5

Table A 5: Amount of precipitation (mm) in Gross Gerau 2011-2019

Cropping season	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July
2011/2012	30.0	2.5	95.2	60.9	6.8	16.5	40.3	76.3	119.7	76.4
2012/2013	59.4	49.0	83.2	34.6	40.2	32.8	75.3	138.0	59.6	13.1
2013/2014	111.1	70.4	30.8	40.2	40.4	19.2	30.2	61.9	27.5	85.5
2014/2015	76.9	58.1	58.3	69.6	26.1	23.7	24.5	20.1	65.4	36.3
2015/2016	18.5	68.8	32.5	59.8	74.7	48.5	70.0	122.6	111.2	55.1
2016/2017	70.2	43.5	9.2	18.1	17.4	32.1	12.3	81.9	48.6	112.6
2017/2018	42.8	97.9	75.7	69.5	13.1	47.9	69.5	29.4	33.0	14.4
2018/2019	4.6	27.2	90.7	36.9	5.7	41.4	47.9	86.3	38.5	55.2
Long-term	53.3	52.1	52.4	37.6	34.7	40.7	40.5	60	65.4	66

Table A 6: Average of air temperature (°C) in Gross- Gerau 2011-2019

Cropping season	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Average
2011/2012	10.8	5.6	5.8	1.6	2.2	6.2	14.0	16.1	18.6	18.0	9.89
2012/2013	9.4	6.1	3.5	4.2	-0.3	9.1	10.4	16.8	17.6	19.6	9.64
2013/2014	11.5	5.5	4.0	1.8	0.8	2.6	10.0	12.8	17.7	21.9	8.86
2014/2015	12.6	7.2	3.7	4.3	5.2	8.4	13.3	14.2	18.5	21.0	10.84
2015/2016	9.3	8.0	6.7	3.3	4.7	5.6	9.4	14.8	18.3	20.6	10.07
2016/2017	9.3	5.0	2.1	-1.3	4.9	9.1	9.4	15.7	20.1	20.5	9.48
2017/2018	11.7	5.8	3.8	5.9	-0.2	4.8	14.2	17.8	20.9	23.0	10.77
2018/2019	13.4	6.4	4.5	1.9	4.1	8	11.3	12.6	21.1	21.2	20.4
Long-term	9.7	5.1	2.2	1.1	1.9	5.7	9.8	14.2	17.5	19.3	8.62

Table A 7: Sum of air temperature > 0° C Rauischholzhausen 2015-2018

Cropping season	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Sum
2015/2016	276.0	232.0	221.3	105.3	116.1	146.7	254.5	443.8	525.0	598.3	2919.0
2016/2017	275.9	135.5	83.7	19.2	109.7	246.8	258.2	455.2	554.4	595.9	2734.5
2017/2018	364.5	177.3	121.4	158.2	17.6	139.6	397.1	518.4	563.7	659.1	3116.9

Table A 8: Sum of precipitation (mm) in Rauischholzhausen 2015-2018

Cropping season	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Sum
2015/2016	36.0	82.9	33.2	51.6	61.6	53.0	43.3	46.7	88.6	38.8	535.7
2016/2017	55.8	89.0	7.2	19.0	26.1	32.7	18.3	77.9	27.1	115.7	468.8
2017/2018	21.3	51.6	77.9	103.2	8.9	46.4	57.8	80.0	20.3	30.7	498.1

Table A 9: Average of air temperature (°C) in Rauischholzhausen 2015-2019

Cropping season	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Average
2015/2016	8.8	7.7	7.1	2.7	1.9	5.3	9.1	13.2	16.7	20.3	9.3
2016/2017	8.9	4.0	1.9	-1.9	3.8	8.0	8.2	14.7	18.5	19.2	8.5
2017/2018	11.8	5.5	3.9	5.1	-1.0	3.8	13.2	16.7	18.8	21.3	9.9
Long-term	8.8	4.1	1.0	-0.2	-0.1	4.0	8.0	12.9	15.7	16.9	7.1

Table A 10: NOD, precipitation sum and global radiation sum in Giessen 2012-2019

year_ sowing time	yield hybrids (dt/ha)	yield lines (dt/ha)	hybrids diff. 1. to 2. sowing time	lines diff. 1. to 2. sowing time	diff. Yield hybrids to yield lines	total NOD	total NOD sowing-Dec.	total NOD Jan.-harvest	NOD <0°C	NOD <5°C	NOD >5°C	NOD >5°C Jan.-harvest	NOD >5°C sowing-Dec.	NOD> 10°C	NOD >15°C	NOD >20°C	percipitation Jan.-Aug.	percipitation Mar.-Aug.	percipitation May-Aug.	Global Radiation (kWh/m^2)	Global Radiation (kWh/m^2) Mar.-harvest
2012_1	86,3	64,4	-0,3	-10	21,9	317	95	222	23	84	232	175	57	114	74	24	344,9	275,7	234,8	889350	708731
2012_2	86,6	74,4			12,2	287	65	222	23	81	206	175	31	114	74	24	344,9	275,7	234,8	822055	708731
2013_1	98,7	97,5	-1,9	5,9	1,2	319	91	228	48	117	202	146	56	118	73	31	371,7	310,2	237,0	889663	748242
2013_2	100,6	91,6			9	289	61	228	48	114	175	146	29	118	73	31	371,7	310,2	237,0	829033	748242
2014_1	113,4	113,8	6,7	7,6	-0,4	322	91	231	6	79	243	188	55	136	86	31	448,7	374,3	301,5	928396	783241
2014_2	106,7	106,2			0,5	292	61	231	6	78	214	188	26	136	86	31	448,7	374,3	301,5	880371	783241
2015_1	77,1	72,8	-6,1	0,2	4,3	306	92	214	14	100	206	144	62	107	62	24	280,4	210,1	136,4	887573	753386
2015_2	83,2	72,6			10,6	276	62	214	14	100	176	144	32	107	62	24	280,4	210,1	136,4	839380	753386
2016_1	100,3	94	-3,9	-0,7	6,3	305	85	220	7	85	220	158	62	109	81	23	418,2	304,9	215,2	807664	679555
2016_2	104,2	94,7			9,5	277	57	220	7	80	196	158	38	109	81	23	418,2	304,9	215,2	766143	679555
2017_1	83,5	83,9	9,4	10	-0,4	313	86	227	36	94	219	173	46	118	86	32	474,4	422,2	362,3	890296	741611
2017_2	74,1	73,9			0,2	289	62	227	36	94	195	173	22	118	86	32	474,4	422,2	362,3	847884	741611
2018_1	109,1	104,1			5	286	74	212	26	95	191	154	37	114	89	40	403,2	302,8	225,7	867239	750164
2019_1	94,4	91,5	4,7	4,7	2,9	307	95	212	19	89	218	153	65	98	72	35	296,3	242,3	152,2	909193	726481
2019_2	89,7	86,8			2,9	286	74	212	19	89	197	153	44	98	72	35	296,3	242,3	152,2	850665	726481
mean	93,9	88,1	1	3	6	298	77	221	22	92	206	162	44	114	77	29	378,2	305,5	233,6	860327	735511

Table A 11: NOD, precipitation sum and global radiation sum Gross Gerau 2012-2019

year_ sowing time	yield hybrids (dt/ha)	yield lines (dt/ha)	hybrids diff. 1. to 2. sowing time	lines diff. 1. to 2. sowing time	diff. Yield hybrids to yield lines	total NOD	total NOD Jan.-harvest	total NOD sowing-Dec.	NOD <0°C	NOD <5°C	NOD >5°C	NOD >5°C Jan.-harvest	NOD >5°C sowing-Dec.	NOD> 10°C	NOD >15°C	NOD >20°C	percipitation Jan.-Aug.	percipitation Mar.-Aug.	percipitation May-Aug.	Global Radiation (kWh/m^2)	Global Radia-tion (kWh/m^2) Mar.-harvest
2012_1	66,49	64,84	-10,90	-10,26	1,65	303	201	102	19	60	233	164	79	107	69	21	358,8	291,1	234,3	858175	633219
2012_2	77,39	75,09			2,30	280	201	79	19	60	212	164	48	107	69	21	358,8	291,1	234,3	788803	633219
2013_1	94,66	91,40	1,93	5,16	3,26	299	204	95	40	115	181	123	61	100	54	22	387,0	312,2	204,1	836886	670448
2013_2	92,73	86,24			6,49	272	204	68	40	115	157	123	34	100	54	22	387,0	312,2	204,1	774755	670448
2014_1	72,19	70,59	6,11	3,86	1,60	296	198	98	5	73	217	160	63	114	64	20	285,8	205,2	155,8	858547	672414
2014_2	66,09	66,73			-0,64	269	198	71	5	73	196	160	36	114	64	20	285,8	205,2	155,8	799720	672414
2015_1	85,26	83,53	7,88	8,44	1,74	284	197	87	11	91	193	136	57	98	54	22	234,9	139,2	91,0	819325	689111
2015_2	77,39	75,09			2,30	256	197	59	11	91	165	136	29	98	54	22	234,9	139,2	91,0	780034	689111
2016_1	83,69	82,64	0,84	-0,42	1,05	289	208	81	7	76	213	157	56	101	67	22	536,9	402,4	283,9	796246	664739
2016_2	82,86	83,06			-0,20	261	208	53	7	71	190	157	33	101	67	22	536,9	402,4	283,9	758620	664739
2017_1	61,48	59,23	0,35	1,40	2,25	294	212	82	32	89	205	163	42	115	76	37	283,8	248,3	203,9	856260	714153
2017_2	61,13	57,83			3,30	272	212	60	32	88	184	163	21	115	76	37	283,8	248,3	203,9	824955	714153
2018_1	51,46	54,65			-3,19	261	186	75	21	83	178	139	39	91	70	34	262,4	179,8	62,4	744024	613944
2019_1	73,12	69,97	16,33	13,81	3,15	288	204	84	16	73	215	159	56	104	66	28	290,9	248,3	159,0	921161	749891
2019_2	56,79	56,16			0,63	266	204	62	16	73	193	159	34	104	66	28	290,9	248,3	159,0	873090	749891
mean	73,51	71,80	3,22	3,14	1,71	279	202	77	19	82	195	151	46	105	65	25	334,6	258,2	181,8	819373	680126

Declaration

I declare: I have prepared the submitted dissertation independently and without unauthorized outside help and only with the help that I have indicated in the dissertation. All text passages taken verbatim or in spirit from published writings and all information based on oral information are marked as such. In the research conducted by me and mentioned in the dissertation, I have complied with the principles of good scientific practice as laid down in the "Statutes of the Justus Liebig University Giessen for the safeguarding of good scientific practice.

Gießen, 08/06/2023

Yazdan Vaziritabar