



**Novel selection criteria for drought tolerant winter
wheat genotypes and their correlations to drought
stress indicators, crop development, plant morphology,
yield and quality parameters**

Master Thesis

To obtain the academic degree of
Diplom-Ingenieur (Dipl.-Ing.)

submitted by:

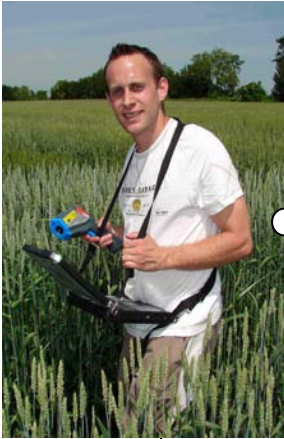
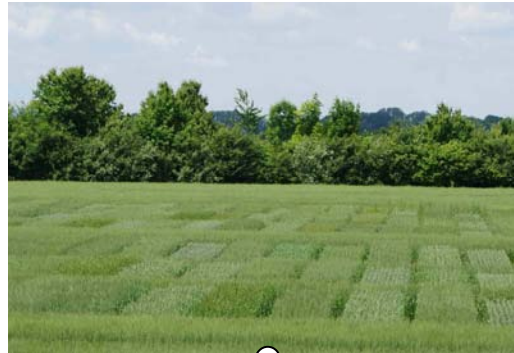
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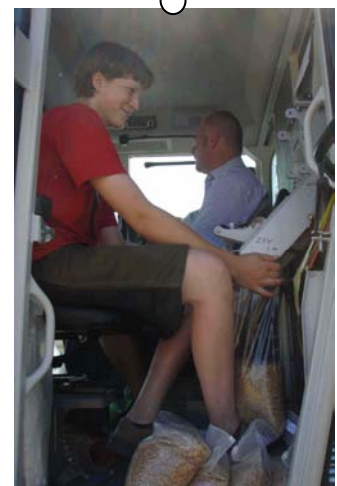


Sweet is the memory of past struggle.

Süß ist die Erinnerung an vergangene Mühen.

Suavis laborum est praeteritorum memoria.

(Cicero, Euripides – De finibus bonorum et malorum 2. 195)



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LIST OF ABBREVIATIONS

BBCH = Phenological growth stages and BBCH-identification keys of cereals

p = p-value

Bre = Breitstetten (in figures and tables blue colour)

Tat = Tattendorf (in figures and tables red colour)

St. A = St. Andrä (in figures and tables yellow and dark yellow colour)

EKA = Electrical capacitance of roots (nF)

OSP = Flag leaf osmotic potential (MPa)

OTE = Flag leaf canopy temperature (°C)

SPD = Flag leaf chlorophyll content (SPAD units)

STO = Flag leaf stomatal conductance ($\text{mmol m}^{-2} \text{s}^{-1}$)

BLRO = Leaf rolling (scale 1 - 9)

SZF1 - 3 = Leaf senescence at the first, second or third scoring date

DTAE = Heading date

DTBL = Date of anthesis

DTGR = Date of physiological grain maturity

WHOE = Plant height (cm)

BEST = Ear density (number of ears m^{-2})

KOEQ = Grain yield (dt ha^{-1} , 86 % dry matter)

HLGW = Test weight (kg)

TKGN = Thousand grain weight (g, 86 % dry matter)

RPRT = Grain protein content (%)

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1. INTRODUCTION

Wheat (*Triticum aestivum* L.) is grown in most parts of the world and the amount of wheat traded internationally exceeds that of all other grains. The worldwide cultivation area accounts for 223,564,097 ha and the yield averages out at 3,086 kg ha⁻¹ (FAO, 2008).

Because of the importance of this crop it is necessary to ensure a stable yield everywhere in the world. During the past few years wheat production fluctuated enormously. One important reason was climate change, more precisely drought.

Many definitions exist for the term drought. According to Reynolds et al. (2005) drought occurs when the soil moisture is below the water amount a particular crop needs at a particular time. In addition the term could also be used for characterizing a region. Namely, if water availability decreases below the statistical requirements for a region, this region will be at risk of drought. Blum (1988) defined drought stress as the “inability of the crop to meet its evapotranspirational demand”.

Further on, the term drought is mostly used in connection with the yield. Here, different points of views are possible (Oberforster and Flamm 2007). On the one hand drought tolerance is the ability (of a genotype) to maintain physiological activity during drought stress and therefore to maintain high yields. This approach is mainly important for farmers and the entire chain from agricultural production to the enduser. On the other hand drought tolerance can be evaluated through the absolute (dt ha⁻¹) and relative (%; referring to the yield of the control) reduction in yield. In case of late-season drought stress, this decline in output is due to a reduced grain number per ear and a lower thousand grain weight. According to Oberforster and Flamm (2007) the third point of view is concerned with stable and high yields under water deficit. One indicator for yield stability is the standard deviation of relative yields (Schwarzbach 1989).

Especially in hot arid environments with high solar radiation, water deficit is a major problem. So many farmers react to drought with irrigation in order to obviate enormous reductions in wheat yield. Because of the consequential soil salinization, alkalization (Szabolcs 1994) and high costs for installing respectively maintaining the artificial rain system, irrigation only serves as a short term solution. The limiting factor is water.

Now it is the breeder's task to react to climate change and create genotypes that can cope with less water availability and show a higher drought tolerance. These adapted varieties should at least bring the same yield as wheat varieties without drought stress or even outyield them. For improving crop yield under limited water supply many experiments have already been performed, observations have been made and many publications exist (Collins et al. 2008, Condon et al. 2004, Richards et al. 2002). However, until now it was not possible

to detect screening methods for finding drought tolerant wheat varieties. The problem is that drought tolerance is an extremely complex trait. The plant responses depend on growth stage when drought occurs, on intensity of drought (Oberforster et al. 2008, Frank and Bauer 1984, Angus and Moncur 1977, Levitt 1972) and on additional prevailing biotic and abiotic stresses (Reynolds et al. 2005).

Recently, conventional breeding methods were amended with bio-molecular methods. Thus it is possible, not only to select and cross high yield varieties with robust, drought tolerant varieties, but also to transfer genes that are responsible for forming stress tolerance into crops that are grown in arid environments. However, these Genetically Modified Organism (GMO) have no license for release and cultivation in Austria and therefore breeding companies are still challenged. The need for drought tolerant cultivars is huge and their finding, with the help of effective selection criteria, is indispensable.

Because of this importance, a research project called “Winter wheat cultivars maintaining high yield under environmental stress” has been set up on 1st of October 2009 and will last for 2 years. The participating countries are Germany, Hungary and Austria. This project is conducted within the frame of a CORNET programme, which stands for COLlective Research NETworking. Its aim is to set up the cooperation and coordination of research activities between the responsible national or regional ministries and agencies. Furthermore it creates opportunities to set up transnational collective research with national or regional funding. It is supported by the European Commission and each partner has its own financing agency in its country. In Austria it is the Austrian Research Promotion Agency (FFG) which is located in Vienna.

The objectives of this project are divided into three work packages. The first one contains the phenotypic and genotypic evaluation and the management and design of the field trials. The second work package covers the assessment of baking quality parameters. The last package includes the molecular mapping of drought/heat Quantitative Trait Loci (QTL). Summing up we might say that this project focuses on detecting winter wheat varieties that are drought tolerant.

Unfortunately the weather conditions were bad this year and the climate was affected by precipitation surplus from March to the middle of June. Additionally the temperature was low during this time period and therefore there was hardly any a chance to face drought stress. Due to this difficult situation, the original title of this thesis as well as the objectives had to be modified. A comparison of drought stressed wheat genotypes with genotypes that were well supplied with water, was not possible any more. The new direction of the thesis had a focus on the usefulness and reliability of selection criteria for detecting drought tolerant varieties.

Within this master's thesis only the data and results of Austria will be presented and discussed.

1.1. Literature

1.1.1. General information

Drought stress and its effect on crops is one of the most serious limitations to maximum wheat production world wide (Jones and Corlett 1992). Already in the early 19th century and up to now an increasing number of researchers have been questing for plant responses to drought stress, breeding drought tolerant varieties and finding screening methods that can be used in practical plant breeding programs. Seelhorst (1899) was one of the first researchers who studied the water consumption of oat at different water contents and fertilization stages. The search for varieties with improved resistance to abiotic stresses is a major goal of plant breeders and researchers all over the world. The complexity of drought itself (Passioura 2007, 1996), of the stress responses as well as the large number of genes and gene products that are involved in these responses makes it so difficult to find a means for combating this restraint.

In many cases, plants are challenged with several classes of abiotic environmental stress (Jones et al. 1989). Especially under water shortage crops are exposed to a combination of stresses including a large number of climatic factors (Kreeb 1974). Drought and heat stress are often linked, caused by high temperature, water shortage, excessive irradiance or low water potential. According to Szabolcs (1994) poor soil conditions also lead to stress, especially if the soil is resistant to root penetration.

All of these different types of stress can occur at the same time and it is nearly impossible to find selection criteria just for one specific type of stress. Additionally the characteristic of the traits can vary depending on stress intensity, stress duration, the plant's age and other opportunities of environmental stress and therefore the trait characteristic is non-reproducible.

1.1.2. Adaptation mechanisms to drought stress

Plants respond to water deficit with physiological, biochemical and molecular changes. These adaptations are complex and diverse mechanisms (Jones 2004, Chaves et al. 2003, Hall 2001, Nilsen and Orcutt 1996, Blum 1988, Jones et al. 1981, Levitt 1980).

The classification of these mechanisms was developed by Levitt (1972) and is vitally important till this day: (i) drought escape, (ii) dehydration avoidance and (iii) dehydration tolerance.

The first mentioned method (i) is characterized through a rapid development which allows plants to reach maturity before severe drought stress (Ludlow and Muchow 1990, Turner 1986a). The flowering phase is reduced and plants can escape from the major drought during grain fill (Slafer et al. 2005, Richards et al. 2002, Bolanos et al. 1993). It is a combination of a short life cycle with a high rate of growth and gas exchange.

Dehydration avoidance (ii) is mainly controlled by osmotic adjustment and the aim is to maintain a higher tissue water or turgor potential under water deficit (Hall 2001, Blum 1988). Of course plants use different strategies to avoid dehydration and a lot of internal processes are involved (Blum 1988). These are for example a reduction of the transpiration rate by the reduction of stomatal conductance (Ray and Sinclair 1997, Ludlow and Muchow 1990) and leaf area (Salih et al. 1999), a change in the release of plant hormones (Blum 1988), an increase in soil moisture capture through amended root growth (Salih et al. 1999), phenotypic changes and consequently an increase in the water use efficiency.

Another response to water deficit is dehydration tolerance (iii). Plants tolerate a long period of low tissue water (Sullivan and Aross 1979) via osmotic adjustment. Through this mechanism growth under drought stress is maintained, but it will also lead to structural changes (Bewley 1979). Reduction of stomatal conductance (Chaves et al. 2003) in order to sustain cell turgor, translocation of assimilates, ear photosynthesis, accumulation of metabolites and stem reserve mobilization (Paul et al. 2004) are the main processes in plants for dehydration tolerance (Blum 1988). Tolerance to water deficit simply means that the plants become water stressed, but are still able to maintain productivity.

1.1.3. Selection criteria

Blum (1988) also specified selection criteria for the selection of drought tolerant cultivars. These are for example, leaf rolling, wilting, leaf firing, canopy temperature, root growth, cell structure, leaf surfaces and grain growth. Although Blum pointed out some possible selection criteria, Jenka (1985) and Hanson and Nelsen (1980) supposed that there are no definite criteria for breeding resistant cultivars. The problems that cause this assumption are mostly a combination of different stresses at the same time, differences in stress intensity and duration and the differences in the reaction to stress.

A lack of fast and reproducible screening techniques is an additional influencing factor that complicates the finding of selection criteria.

However, crop physiological studies under water scarcity presented some indirect traits that could be used for selecting more drought tolerant varieties. These traits are: radiation and water use efficiency, rate of flag leaf senescence, duration of grain filling and green leaf, flowering date or plant height (Araus et al. 2008, Reynolds and Tuberosa 2008).

Selection criteria that were measured and screened within this study are further described below.

Electrical capacitance of roots

Due to the fact that roots have a huge influence on the whole plant development, on the nutrient and water uptake, the electrical capacitance of roots was measured. In several studies and publications, measurements were performed by either a needle plant electrode or a clamp plant electrode (Matsumoto et al. 2001, Ozier-Lafontaine et al. 2001, Chloupek et al. 1999, Van Beem et al. 1998, Dalton 1995, Kendall et al. 1982, Chloupek 1980, Chloupek 1972).

According to Chloupek (1972) and Chloupek et al. (1999) the measured root capacitance values provide an indication of different root parameters, such as root mass, size and length. Increasing root length and therefore a deep penetration in wet soil layers is an effective component of drought resistance (Meyers et al. 1984, Mambani and Lal 1983, Hurd 1968). Furthermore, Chloupek et al. (1999) detected that the water content of the soil has a wide influence on the measured capacitance values.

The electric capacitance values also represent the size of the active root surface (Dalton 1995).

Osmotic adjustment

Osmotic adjustment can be expressed through the osmotic potential. When water is removed from cell, due to drought stress, osmotic potential is reduced and more solutes are concentrated in the cell (Blum 1988). This process of accumulating osmotic particles at given cell volume is so called osmotic adjustment. Plants without this ability can not survive under water deficit (McGowan et al. 1984).

Osmotic adjustment is the main mechanism of drought tolerance and it enables plants to recover faster from water deficit. Further, osmotic adjustment is a metabolic activity of plant cells to tolerate low leaf water potential (Chaves et al. 2003). According to Blum (1988) osmotic adjustment is the accumulation of solutes during water deficit to maintain a higher turgor potential at a given leaf-water potential. This process also protects cells from extreme desiccation and allows continued gas exchange.

The benefit deriving from osmotic adjustment is that through the aperture of the stomata, the photosynthesis rate is still high. Another advantage is the low leaf water potential through which the plant can get slightly more water from the soil (Sharp et al. 2004, Hall 2001).

Morgan (1983) illustrated that genotypes with a higher osmotic adjustment were more profitable than varieties with a low osmotic adjustment under drought conditions.

Canopy temperature

Canopy Temperature, more precisely Canopy Temperature Depression (CTD = canopy temperature minus air temperature), has been used as a selection criteria in wheat breeding. According to Reynolds et al. (2001) biological and environmental factors affect the CTD. These factors are for instance, cloudiness, wind, air temperature, plant metabolism, stable and continuous radiation and relative humidity.

Munjal and Rena (2003) reported that during the grain fill phase, cool canopy is an important benefit and it indicates a stress tolerance for high temperature. However, Hatfield et al. (1987) proposed, that genotypes with low canopy temperatures are preferred as long as there is no risk of late-season drought stress. Under such conditions, genotypes which can handle the water availability more economically, namely genotypes with higher canopy temperatures, would be appropriate.

Chlorophyll content

So far, experiments and publications proved that drought stress also influences the chlorophyll content. Generally speaking, water deficit leads to an increased depletion of chlorophyll and a decreased concentration of chlorophyll. According to research results of Izanloo et al. (2008) chlorophyll content increased under drought conditions until the stage of anthesis in all varieties. Additionally there was a positive correlation between grain size and chlorophyll content: Varieties with higher chlorophyll content also resulted in a higher grain size.

During the stage of grain filling drought sensitive genotypes experience a loss in their photosynthesis capacity, due to a deficit in chlorophyll of the synthesizing organs (Reynolds et al. 1992).

Stomatal conductance

Because of the fact, that the leaf canopy temperature is a function of stomatal conductance (Blum 1989), great importance should be attached to stomatal control too. The closure of stomata is an early and one of the first responses of plants to water scarcity under field conditions and it is affected by temperature (Jones 1992). During stomata closure the flow of water is reduced, photorespiration is increased (Nilsen and Orcutt 1996) and the carbon uptake by the leaves is limited (Cornic and Massacci 1996, Chaves 1991). It seems that the stomatal responses are connected with the leaf water status, though several experiments indicated the relation to soil moisture content and chemical signals (Davies and Zang 1991, Gowing et al. 1990). Reynolds et al. (1998) enhanced the assumption of a correlation between stomatal conductance and soil moisture content. More precisely, a low canopy

temperature and high stomatal conductance indicate higher soil moisture content and a deeper rooting system.

Leaf rolling and leaf senescence

Leaf rolling and leaf senescence are traits that emerge as a response to water deficit, especially in crops (Tardieu 2005, Hsiao et al. 1984). Furthermore, these two traits are methods to reduce the leaf size and to decrease the evapotranspiration. This would lead to the assumption that genotypes which roll the leaves earlier could be the better adapted ones as far as drought stress is concerned. On the other side, a smaller canopy absorbs less radiation and this will lead to less production of dry matter (Loss and Siddique 1994).

Leaf rolling is the result of turgor loss and it occurs at a lower leaf-water status in osmotically adjusted leaves. Nevertheless, leaf rolling depends on the variety too. Genotypical differences in the leaf morphology as well as the willingness to roll the leaves are important influencing factors (Jones 1979). Delayed leaf rolling is used as an important selection criterion for dehydration in rice (IRRI 1982, O'Toole and Cruz 1979) and maize (Sobrado 1987).

According to Thomas and Howarth (2000) plants that stay green longer, experience a delayed leaf senescence. This trait enables the plant to maintain more photosynthetic active leaves. Under post-anthesis drought conditions, grain yield and quality can be increased.

Date of heading, flowering and physiological grain maturity – drought stress at different growth stages

The plant's stage of development that is exposed to drought stress has an important effect on the damage experienced by the plant (Slafer and Rawson 1995). For reducing these damages in case of late drought stress early maturing genotypes which can escape from water scarcity should be chosen (Ludlow and Muchow 1990).

If water deficit already occurs during the vegetative stage a reduced leaf area and because of this a reduced carbon gain as well as effects on tillering and ear size are the consequences (Nilsen and Orcutt 1996, Sandha and Harton 1977, Mayaki et al. 1976). Water shortage at the beginning of stem elongation leads to few ears (Sangtarash 2010).

The flowering stage from booting to flowering is a very sensitive crop stage to water scarcity (Kirda et al. 1999). As a consequence drought stress occurring seven days before and also at the date of anthesis causes a reduced number of grains per ear (Fischer 1980, Canny 1960).

Water scarcity after anthesis usually leads to smaller seed size (Mirbahar et al. 2009, Jamieson et al. 1995). This is due to accelerated flag leaf senescence (Hafsi et al. 2000, Evans et al. 1970).

Relating to corn yields research results verified that poorest yields were achieved when drought stress emerged at flowering (Sangtarash 2010, Mirbahar et al. 2009, Pirayvatlou 2001). High yields can be reached when the growth stages of booting and flowering, heading and milking are provided with sufficient quantities of water (Kirda et al. 1999).

Plant height

According to Blum (1988) plant height is no selection criterion for drought resistant varieties. Furthermore it was supposed that the height influences the root growth and the soil-moisture extraction, but several studies disproved this assumption (Holbrook and Welsh 1980, Pepe and Welsh 1979).

Current research papers concluded that drought has a bearing on the plant height. Well watered varieties are taller than plants that are subjected to drought stress (Izanloo et al. 2008). Additionally, tall genotypes resulted in a higher decrease in yield than dwarfish genotypes under stress conditions (Oberforster and Flamm 2008).

The above described indirect traits that were already found in literature were newly categorized in this master's thesis. The chlorophyll content, the canopy temperature, the stomatal conductance, the osmotic adjustment and the electrical capacitance of roots were combined under the term "novel selection criteria". The next category "stress indicators" include the leaf rolling and leaf senescence. The date of heading, flowering and maturity as well as the plant height were classified into "growth stages and plant morphology".

1.1.4. Correlations

Technical literature shows significant interactions between the selection criteria and the growth stages, the plant height, the yield and the quality parameters. With the help of these correlations, traits can be determined that will help to direct the breeding programs towards genotypes that maintain high yield under environmental stress (Kandić et al. 2009).

First, interactions regarding some selection criteria (stomatal conductance, canopy temperature, chlorophyll content, senescence rate, osmotic adjustment, days to heading, flowering and maturity, plant height) were detected. After that, correlations will follow that put emphasis on the grain yield and the yield components (ear density, ears per plant, grains per ear, thousand grain weight) mainly under drought conditions.

Izanloo et al. (2008) and Reynolds et al. (2001) reported a significant negative correlation between the stomatal conductance and the canopy temperature. A correlation of low canopy temperature and high transpiration rate (and high stomatal conductance) was detected by

Blum (1989) too. However, under irrigated treatment the relationship between the stomatal conductance and the leaf temperature was non significant (Izanloo et al. 2008). According to Bunce (1981) and Shimshi and Ephrat (1975) the stomatal conductance was further positively correlated to the yield in various crop varieties.

Another relationship regarding the stomatal conductance was reported by Reynolds et al. (1998). They noticed an association between a low canopy temperature or high stomatal conductance and a deeper rooting system, which can take up more soil moisture.

A positive correlation between the chlorophyll content and the yield was found by Gutierrez-Rodriguez et al. (2004) and Borrell et al. (2000) under irrigated and drought conditions. This positive correlation was reported by Tahiro (2002) and Reynolds et al. (1992) too, but only under heat stress conditions. Izanloo et al. (2008) reported a significant positive correlation between the chlorophyll content and the grain size. The chlorophyll content showed further negative interactions with the leaf senescence. Munné-Bosch and Alegre (2004), Lu et al. (2002) and Lu and Zhang (1998) noticed that during drought stress, this connection could be a type of programmed cell death in order to survive under drought conditions.

An association between the osmotic adjustment and therefore the osmotic potential with a delayed leaf rolling has been detected by Steponkus et al. (1982), Turner and Jones (1980), Cutler et al. (1980a, 1980b) and Hsiao et al. (1976).

Stay green cultivars (varieties with a low senescence rate) were negatively correlated with the grain size (Spano et al. 2003). Larger grains can be produced through an extended period of flag leaf photosynthetic capacity during grain-filling.

The days to heading were significantly associated in a negative way with the spike length, the thousand grain weight and the grain yield under irrigated conditions as well as under drought conditions (Subhani and Chowdry 2000). A positive relation was noticed between the days to heading and the ears per plant.

According to Asif et al. (2004) the days to maturity were positively correlated with the grain yield. This association was detected by Anwar et al. (2009) under irrigated conditions. Additionally they reported another positive relationship between the days to maturity and the ears per plant as well as for the thousand grain weight. No correlation was found between the days to maturity and the plant height (Akram et al. 2008).

According to Subhani and Chowdry (2000), Akhtar et al. (1992) and Bhatt (1973) the plant height was positively associated with the thousand grain weight and the ears per plant. This was also reported by Akram et al. 2008, Belay et al. 1993, Eunus et al. 1986 and Sandhu and Mangat 1985. The plant height was negatively correlated with the grain yield (Akram et al. 2008, Khaliq et al. 2004, Okuyama et al. 2004, Patil and Jain 2002, Shahid et al. 2002,

Akbar et al. 1995, Chaudry et al. 1994, Li 1989, Ahmad et al. 1980) under irrigated and drought conditions.

The ears per plant were significantly correlated in a positive way with the biomass per plant (Singh et al. 1990), the harvest index and the grain yield (Saleem et al. 2006, Ahmad et al. 1994, Krotova 1988) under irrigated and drought conditions. Under drought conditions, Krotova (1988) detected negative associations between the ears per plant and the plant height, the ear length, the grains per ear and the thousand grain weight.

The correlation between the ear density and the grain protein content was positive (Zečević et al. 2004).

Tiwari and Rawat (1993) reported that there were significant positive interactions between the grain yield and the ear length, the ears per plant (Anwar et al. 2009, Aycecik and Yildirim 2006, Usman et al. 2006, Lad et al. 2003), the spikelets per ear and the ears per plant. These correlations were partially confirmed by Sharma et al. (1995). Additional positive correlations were found between the grain yield, the grains per ear and the harvest index. Singh et al. (1995) reported further positive correlations between the grain yield and the thousand grain weight. This positive association was also observed by Akram et al. (2008), Aycecik and Yildirim (2006), Inamullah et al. (2006), Baser et al. (2000), Narwal et al. (1999), Uddin et al. (1997), Akbar et al. (1995), Hossain (1995) and Mikheev (1992). Wang et al. (1991) reported the same positive interaction between the grain yield and the thousand grain weight under irrigated conditions.

Subhani and Chowdhry (2000) as well as Sheoran et al. (1986) reviewed that the grain yield was positively correlated with the flag leaf area, the thousand grain weight, the ear length, the ears per plant (Akram et al. 2008), the grains per ear, the biomass per plant and the harvest index under normal, drought and rainfed conditions.

Nevertheless, Subhani and Chowdhry (2000) and Sheoran et al. (1986) found positive associations between the grain yield and the plant height, although this correlation was reported in a negative way by several other researchers (Akram et al. 2008, Khaliq et al. 2004, Okuyama et al. 2004, Patil and Jain 2002, Shahid et al. 2002, Akbar et al. 1995, Chaudry et al. 1994, Li 1989, Ahmad et al. 1980).

Negative interactions regarding the grain yield and the days to heading and maturity were detected by Subhani and Chowdhry (2000) and Singh et al. (1995).

Another significant negative correlation was found between the grain yield and the days to flowering and leaf senescence (Kandić et al. 2009) under irrigation and drought stress.

1.2. Objectives of the study

Because of increasing drought damages on crops especially in the east of Austria where semi-arid climate predominates, it is essential to detect varieties that are well adapted to water shortage. Hence, the objective of this study is to determine effective and reliable selection criteria for selecting drought tolerant genotypes. The focus is on the novel selection criteria and their correlations to drought stress indicators, growth stages, plant morphology and yield.

The hypothesis is devised as follows:

H_0 = Novel selection criteria can be used for detecting drought tolerant winter wheat genotypes.

By means of this hypothesis more detailed issues can be posed:

- There are interactions among the novel selection criteria.
- Novel selection criteria are correlated with stress indicators.
- There are correlations between the novel selection criteria and the growth stages and plant morphology.
- Novel selection criteria are correlated with yield and the quality parameters.
- There are interactions among the stress indicators.
- Stress indicators are correlated with growth stages and plant morphology.
- Correlations between stress indicators and yield and the quality parameters exist.
- The growth stages as well as the plant morphology are correlated with the yield and the quality parameters.

2. MATERIAL AND METHODS

2.1. Study site and experimental set-up

A field experiment was set up in October 2009 at three locations in Eastern Austria: Tattendorf (Lower Austria, 47°57' N and 16°18' E), Breitstetten (Lower Austria, 48°12' N and 16°45' E) and St. Andrä (Burgenland, 47°47' N and 16°56' E). The climate data of the study sites are shown in Table 1. These data were taken from the meteorological stations next to the study sites and present the longtime average of the period 1971 - 2000.

Table 1: Climate characterization of the three study sites

Location	Tattendorf	Breitstetten	St. Andrä
Meteorological station	Baden	Fuchsenbigl	Neusiedl am See
Sea level (m)	260	149	135
Average annual precipitation (mm)	623	524	574
Mean annual temperature (°C)	9.9	9.5	10.1
Average wind speed (m s ⁻¹)	1.1	2.8	3.0
Mean annual atmospheric humidity (hPa)	9.9	9.4	10.0

(ZAMG, 2010)

The field trials were located in the continental, pannonian climate. This climate is characterized by cold winters and dry, hot summers.

In order to evaluate the different genotypes and their reaction on drought stress, study sites in dry environments were chosen. Another desired effect was soil with a low water holding capacity.

At all three study sites a core set of 25 winter wheat genotypes (Table 2) was planted. These genotypes were proposed from Germany, Hungary and Austria at a ratio of 8:8:8 plus the variety 'Capo' as a standard cultivar in these three countries. Additionally 72 different genotypes were cultivated at the three study sites. These varieties were chosen by the Austrian breeders Saatzucht Edelfhof and Saatzucht Donau. The complete list of genotypes

varied from low to high quality wheat, from drought stress tolerant to drought stress sensitive, from dwarfism to tall varieties and from early maturing to late maturing varieties.

Table 2: Core set of the 25 winter wheat genotypes

Variety	Germination (%)	TGW (g)	Breeder, country	Plant height** (scale 1-9)	Heading** (scale 1-9)	Countries of registration*
Capo	94	46.0	Mauthner, A	7	3	H
Tacitus	93	40.3	Saatzucht Donau, A	3	3	SK
Komarom	93	45.0	Saatzucht Donau, A	3	3	H
Bitop	94	49.0	Saatzucht Donau, A	4	2	H, A
Exklusiv	95	45.0	EHO Saat, A	4	5	A, LU
Eurofit	90	45.0	EHO Saat, A	5	4	CZ, H, A, SI, SK
Midas	95	47.0	Saatzucht Donau, A	5	3	A
Element	88	45.0	EHO Saat, A	6	1	A
Eurojet	90	51.0	EHO Saat, A	6	6	A
GK Petur	95	47.1	CRC, H	4	2	H, RO
GK Kalász	98	42.7	CRC, H	4	1	H, RO
GK Békés	98	41.7	CRC, H	5	1	H
GK Fény	97	39.8	CRC, H	5	1	H
GK Csongrád	95	37.7	CRC, H	6	1	H
GK Szala	94	51.5	CRC, H	6	3	H
GK Rába	94	50.0	CRC, H	7	3	H
GK Hunyad	92	52.3	CRC, H	7	3	H
Robigus	98	52.0	KWS, DE	2	6	IE, NL, UK
Premio	95	52.5	RAGT, DE	3	3	FR
Brilliant	97	43.6	Saatzucht Semundo, DE	4	5	CZ, DE, HU, LT
Hyland	84	51.9	Nordsaat, DE	4	4 - 5	DE
Hybred	92	50.0	Nordsaat, DE	5	6	DE, FR
JB Asano	94	62.0	Saatzucht Breun, DE	5	4	DE, LU
Pegassos	96	60.0	Saatzucht Strube, DE	6	5	DE, LT, A, SI, SK
Tiger	97	52.9	Pflanzenzucht Oberlumpurg, DE	7	5	DE, CH

TGW = thousand grain weight; Breeder: EHO Saat = Saatzucht Edelhof, CRC = Cereal Research Non-profit Company, KWS = Kleinwanzlebener Saatzucht AG (original name), RAGT = Rouergue, Auvergne, Gévaudan, Tarnais (abbreviation of the four regions of origin); Plant height: 1 = very short, 9 = very long; Heading: 1 = very early, 9 = very late;

** = pub. from national Federal Offices, in Austria: Austrian Agency for Health and Food Safety (AGES 2010), in Germany: Federal Offices for Plant Varieties (BSA 2010), in Hungary: Central Agricultural Office (2010);

* = pub. from KOMMISSION, Gazette of the European Union (2009)

The field experiments were arranged in a randomized lattice design with three replications. Plot size differed from location to location. Trials in Breitstetten were established on an area of about 1.75 ha and the net area of each plot was 12.5 m². Tattendorf showed a trial area of

about 1.44 ha. The plot net area there was 13.5 m². St. Andrä was the smallest study site with an area of about 3,332 m² and a net plot area of 8 m².



Figure 1: Field trial in Breitstetten, plots with three replications

2.2. Soil characteristics (BFW, 2010)

2.2.1. Tattendorf

At Tattendorf calcareous black soil is predominant. This soil type is rich in humus (3.15 – 2.52 %), has a medium depth of soil, a high permeability and a low available field capacity (60 – 140 mm) in the mineral soil layer.

The soil texture ranges from clay, clayey silt to sandy clay.

2.2.2. Breitstetten

The chernozemic soil of this region is evolved from calcareous fine sediments. High depth of soil, moderate permeability and a medium available field capacity (140 – 220 mm) in the mineral soil layer are the main characteristics. The soil texture is similar to Tattendorf.

2.2.3. St. Andrä

This study site is located in the shore of the Neusiedler See, in the lake corner. This region is characterized by a dry and hot climate with a moderately calcareous chernozemic soil. Additionally the permeability is high, the available field capacity in the mineral soil layer is low (60 – 140 mm), the depth of soil and humus is middle. The soil texture is clayey sand.

2.3. Management of field trials

2.3.1. Cultivation

The field trials were planted between 15th of October and 2nd November 2009 and the sowing density was 300 grains m⁻². The sowing of the plots was done crosswise to the direction of the cultivation of the remaining field. The reason for this process is to ensure that possible processing impacts influence all plots of one replication in the same way. Other tillage operations, the use of herbicide and fertilization were done according to the local practice and conditions. An overview of the cultivation, fertilization and crop rotation is given in Table 3. Growth regulators were not used at all.

Table 3: Overview of the cultivation, fertilization and crop rotation at all three locations

Location	Date of sowing (mm / dd / yyyy)	Dates of fertilization (mm / dd / yyyy)	Total fertilization (kg N ha ⁻¹)	Previous crop
Tattendorf	10 / 23 / 2009	3 / 10 / 2010 4 / 17 / 2010 5 / 25 / 2010	128.5	Rye (<i>Secale cereale</i>)
Breitstetten	11 / 02 / 2009	3 / 09 / 2010 4 / 29 / 2010 5 / 27 / 2010	140.4	Sorghum (<i>Sorghum bicolour</i>)
St. Andrä	10 / 15 / 2009	3 / 19 / 2010 5 / 07 / 2010	129.6	Potato (<i>Solanum tuberosum</i>)

2.3.2. Pest management

For protecting the plants from late fungal diseases, the product Input from Bayer Crop Science was used. The application rate was one liter Input with 200 to 400 liter water per hectare. The active components of this fungicide are Prothioconazole and Spiroxamine. Due to the greening effect of fungicides the treatment was performed only once. Application time varied from the middle to the end of heading (BBCH 55 - 59), a treatment after heading was avoided.

2.3.3. Harvest

The field trials were harvested with a “Wintersteiger” combine (Figure 2), which has a cutting width of 1.35 m. Harvest time was chosen according to local practice.

In St. Andrä it was done on the 15th of July, Breitstetten followed on the 16th and 17th of July and the plots in Tattendorf were harvested on 22nd and 23rd of July.



Figure 2: Wintersteiger combine, type delta

A sample of each plot was filled in a plastic bag on the harvester (Figure 3). Then all three replications of one genotype were collected and mixed in a bucket (Figure 4). Afterwards samples for examining the moisture content were taken and the remaining grains were filled in paper bags in order to determine quality parameters (Figure 5).



Figure 3: Harvest of 1 plot



Figure 4: Mixing the three replications



Figure 5: Samples for examining the water content (in plastic bottles) and the quality parameters (in paper bags)

2.4. Measurements and screened traits

To specify genotypical differences between the winter wheat varieties each study site was rated for the traits given in Table 4. Trait number one to three and five were visually assessed, trait number four and six to ten were measured and evaluated.

Table 4: Screened traits for each location

Trait	Growth stage (BBCH-identification key) at screening time	Additional specifications
1. Heading date	BBCH 59	<ul style="list-style-type: none"> recorded as calendar date scoring: heads of 50 % of all plants are fully exposed evaluation of each genotype in all replications
2. Date of anthesis	BBCH 65	<ul style="list-style-type: none"> recorded as calendar date scoring: anthers of 50 % of all plants are visible evaluation of each genotype in all replications
3. Date of physiological grain maturity	BBCH 87	<ul style="list-style-type: none"> recorded as calendar date scoring: peduncles of 80 % of all plants are yellow for conforming the visual scoring of peduncles kernels of five heads per entry were checked whether thumbnail dents were irreversible evaluation of each genotype in all replications
4. Plant height	BBCH 71 - 78	<ul style="list-style-type: none"> recorded in cm scoring: soil surface to top of the head without awns evaluation of each genotype in all replications
5. Flag leaf senescence	BBCH 73 - 85	<ul style="list-style-type: none"> recorded in percentage (%) scoring: % of discoloured leaf area across the plot scoring was performed three times evaluation of each genotype in all replications
6. Number of ears m ⁻²	BBCH 83 - 89	<ul style="list-style-type: none"> scoring: the 3rd row of each plot was used to count the number of ears evaluation of each genotype in

		all replications
7. Grain yield	---	<ul style="list-style-type: none"> • recorded in kg plot⁻¹ • then converted into dt ha⁻¹ • evaluation of each genotype in all replications
8. Test weight	---	<ul style="list-style-type: none"> • recorded in kg (per hl) • evaluation of each genotype
9. Thousand grain weight	---	<ul style="list-style-type: none"> • recorded in g • evaluation of each genotype
10. Grain protein content	---	<ul style="list-style-type: none"> • recorded in percentage (%) • evaluation of each genotype

BBCH = abbreviation of the three original organizations: Biologische Bundesanstalt (Biological Federal Institute), Bundessortenamt (Federal Office for Plant Varieties), Chemische Industrie Industrieverband Agrar (Chemical industry, Industry Association of Agriculture)

Furthermore several methods for measuring the dimension of plant responses to water deficit were performed. These measuring methods are also mentioned in literature for comparing drought stressed with non-stressed plants and included the measuring of the electrical capacitance of roots (EKA), the osmotic potential of the flag leaf (OSP), the flag leaf canopy temperature (OTE), the flag leaf chlorophyll content (SPD) and the flag leaf stomatal conductance (STO).

All these measurements as well as the scoring of leaf rolling, leaf senescence, the heading, flowering and maturity date, the plant height, the ear density and the yield were taken in the three replications of the core set. In the supplemental set the number of replications varied from one to three, depending on the screened traits.

The data of the osmotic potential were only recorded in the core set of Tattendorf in all three replications.

Regarding the correlations the input data were average values across all replications. All of these average values were adjusted to the lattice design.

The data of the quality parameters represent the value of one composite sample across replicates.

For structuring the results, the screened traits were separated in four groups:

1. Novel selection criteria – including the electrical capacitance of roots, the flag leaf osmotic potential, the flag leaf canopy temperature, the flag leaf chlorophyll content as estimated by the SPAD meter and the flag leaf stomatal conductance

2. **Stress indicators** – including leaf rolling and leaf senescence
3. **Growth stages and plant morphology** – including the heading date, the date of anthesis, the date of physiological grain maturity and the plant height
4. **Yield and quality parameters** – including the ear density, the grain yield per hectare, the test weight, the thousand grain weight and the grain protein content.

2.4.1. *Electrical capacitance of roots (EKA)*

The electrical impedance of the wheat genotypes was measured with an LCR meter (Figure 6). This device, a 3 Escort ELC 133A LCR meter, can test the inductance (L), the capacitance (C) and the resistance (R) of a component.

Due to the fact that this method should give an indication of the root mass and length, only the electrical root capacitance (C) was measured. This capacitance is the result of a given electric potential and it is the plant's ability to hold an electrical charge accumulating on two parallel conducting plates (Hilhorst 1998).



Figure 6: LCR meter
Escort ELC 133A
(Weclonline, 2010)

The root capacitance measuring arrangement was set up according to Rajkai et al. (2005) and it responded to that of the parallel connected capacitance. The test frequency was 1 kHz.



Figure 7: LCR meter
the plant clamp electrode and the
soil electrode

At each plot the soil electrode was inserted about 10 cm into the soil and the clamp plant electrode was attached to the wheat stem at about 6 - 8 cm around the soil electrode (Figure 7). 4 measurements per plot were made and the average was calculated. In Tattendorf the growth stage of the wheat plants was BBCH 61 and in Breitstetten it was BBCH 81.

2.4.2. Flag leaf osmotic potential (OSP)

For measuring the osmotic potential, which is essential for dehydration avoidance (Blum 1988, Morgan 1984, Blum et al. 1983), the method of vapour pressure osmometry was applied. The samples were processed with a Wescor Vapro 5520 vapour pressure osmometer (Figure 8).



With this method the osmolality, more precisely the total number of solute particles dissolved in one kilogram of solvent, can be determined at room temperature. According to Nobel (1991) the osmolality values can be converted to osmotic potentials through thermodynamic equations.

The microprocessor controls measuring cycle proceeds automatically and takes 80 seconds per sample.

Figure 8: Vapour pressure
Osmometer Vapro 5520
(Wescor, 2010)

Prior to measuring the samples with the vapour pressure osmometer, cell saps had to be prepared. Therefore five flag leaves from each plot were torn off, cut at the leaf base, weighted and put in test tubes with 5 ml distilled water. The test tubes were closed airtight and after four and five hours, the five leaves were weighted again. As soon as there was no gain in weight, full saturation was reached. Afterwards the leaf surface was dried, the leaves were wrapped in aluminium foil and killed in a deep freezer (-18 °C). Before measuring, the leaves were defrosted and the cell saps (shown in Figure 9) were pressed out with a fine pored garlic press. The sample volume for the osmometer was 10 µl.

The flag leaves were collected on a sunny day and the wheat plants' growth stage was BBCH 73.



Figure 9: Cell saps in Eppendorf vessels
(cell sap from 5 flag leaves in each vessel)

2.4.3. Flag leaf canopy temperature (OTE)

According to Gausman et al. (1984) and Harris et al. (1984) another important equipment for pointing out stress responses of plants is the infrared thermometry.

At all study sites the infrared thermometer Scan Temp 490 from Dostmann electronic GmbH (Figure 10) was used for quantifying the canopy temperature.



Figure 10: Infrared thermometer
(Wetterladen, 2010)

The infrared thermometer measures the temperature of an object without contacting it. The configuration detects the emitted infrared energy of the measured object and converts this energy into an electrical signal. The signal is displayed in units of temperature.

The canopy temperature was collected from the average of six flag leaves per plot. The leaf side, either the lower or the upper side which was exposed to the sun, was measured. The thermometer was aimed at the leaf with the infrared lens and after pressing the measurement key the surface temperature was displayed. With the help of two laser points (Figure 11) the target spot size was indicated. Measurements were taken again during strongest insolation, on sunny, cloudless days from 11 am to 3 pm.

The growth stage of the wheat plants was BBCH 69 – 75.



Figure 11: Infrared thermometer
with the two laser points (left) and
the displayed surface temperature (right)

2.4.4. Flag leaf chlorophyll content (SPD)

For screening the flag leaf chlorophyll content, the Chlorophyll Meter SPAD-502 from Konica Minolta Holdings Inc. (Figure 12) was used.

Without damaging the leaf the Chlorophyll Meter measured the amount of chlorophyll present in the plant leaf. The sample was inserted in the sample slot of the measuring head and it was irradiated with red light (wavelength = 650 nanometer) and infrared light (wavelength = 940 nanometer). The absorbance of chlorophyll is high in the red area and extremely low in the infrared area. The light which passes through the leaf strikes the receptor and this



transmitted light is converted by the receptor into analog electrical signals. Afterwards the signals are displayed as SPAD values.

From each plot 10 flag leaves were measured and the average was calculated.

The chlorophyll content was detected during the growth stage BBCH 59 – 65 of the wheat cultivars.

Figure 12: SPAD-502 from Konica Minolta
(Konica Minolta, 2010)

2.4.5. Flag leaf stomatal conductance (STO)

The flag leaf stomatal conductance was measured with the leaf porometer from Decagon Devices, Inc.

The leaf porometer uses two humidity sensors with a known conductance. The conductance of the leaf is put in series with these two known conductance elements. The porometer measures then the humidity difference across one of the known conductance elements and so the water vapour flux is obtained. By means of these variables the conductance of the leaf can be calculated.

For measuring the stomatal conductance of the wheat plants, three flag leaves of each plot were screened. The sensor head was put on the flag leaf as shown in Figure 13 and a measurement was completed after 30 seconds.



Figure 13: Leaf porometer and the application of the sensor head

Measurements were taken on sunny, cloudless days from 11 am to 3 pm during strongest insolation.

Only flag leaves that were exposed the most to the sun and fully expanded were chosen. The growth stage of the selected wheat plants was BBCH 65 – 71.

2.5. Meteorological data

To receive meteorological data nearby weather stations and additional local weather stations (Figure 15) for each study site were used. With the local weather stations, soil and air humidity, soil and air temperature as well as precipitation were measured. Precipitation was measured with a rain gauge, more precisely with a precipitation pulse transmitter. It is a tipping bucket rain gauge system (Figure 14) and it collects the falling precipitation. Each tipping is recorded in the datalogger as an event representing 0.35 l m^{-2} of rainfall. The data are saved on a battery supplied built-in datalogger.



Figure 15: Local weather station for measuring precipitation, air and soil temperature and air and soil humidity



Figure 14: The tipping bucket rain gauge system

The stations were installed at a height of 1 m. The given period of time was beginning of April to mid of July 2010.

The distribution of precipitation for each study site is given in Table 5. It is compared to the longtime average of the period 1971 - 2000.

Table 5: Distribution of precipitation for each location from April to July 2010

	Breitstetten		Tattendorf		St. Andrä	
Month (2010)	Precipitation (l m ⁻²)	Difference to the longtime average (Fuc)	Precipitation (l m ⁻²)	Difference to the longtime average (Bad)	Precipitation (l m ⁻²)	Difference to the longtime average (Neus)
April	65.1	+ 19.4 l m ⁻²	53.0	- 2.2 l m ⁻²	56.2	+ 14.0 l m ⁻²
May	116.1	+ 65.2 l m ⁻²	75.5	+ 13.6 l m ⁻²	158.8	+ 97.4 l m ⁻²
June	93.8	+ 24.2 l m ⁻²	76.0	+ 5.6 l m ⁻²	96.9	+ 32.0 l m ⁻²
July	87.2	+ 23.0 l m ⁻²	104.0	+ 37.1 l m ⁻²	74.6	+ 11.0 l m ⁻²

Fuc = meteorological station in Fuchsenbigl, Bad = meteorological station in Baden, Neus = meteorological station in Neusiedl / See

2.6. Statistical analysis

SPSS 16.0 was used for the statistical analysis (SPSS Inc.). For analyzing the variation among factors and their interactions the Analysis of Variance (ANOVA), more precisely the General Linear Model (GLM) with an univariate variable, was used. Correlations were detected through the bivariate correlations by Pearson and a two-tailed significance test. Leaf rolling was rank-correlated using Spearman's approach.

3. RESULTS

The presented results pay attention primarily to the core set. The results of the additional 72 wheat genotypes were always compared with the core set but just shortly discussed. Only if there were substantial differences to the results of the core set they were highlighted.

3.1. Physiological traits

3.1.1. Novel selection criteria

According to the analysis of variance (ANOVA) there were significant differences ($p \leq 0.05$) between the varieties in relation to most of the novel selection criteria (Table 6 and Table A 1). In the core set and the additional 72 genotypes, the electrical capacitance of roots did not show significant differences. There was also no significant genotype effect noticed on the canopy temperature of the supplemental set.

Large variations among the locations were detected for all measured traits. Significant interactions between the varieties and the locations were given for the chlorophyll content, the canopy temperature and the electrical capacitance of roots.

Table 6: Analysis of variance F values of the novel selection criteria

Factors	Dependent Variables									
		EKA		OSP		OTE		SPD		STO
Variety		1.56	*	3.20	*	2.83	*	126.40	*	2.79
Location	*	775.05		---	*	60.42	*	92.00	*	33.06
Variety x Location	*	1.70		---	*	2.83	*	4.91		1.51

* = significant at a level of $p \leq 0.05$

Electrical capacitance of roots (EKA)

No significant genotype effect was noticed for the electrical capacitance of roots (Table 6).

Among the locations large variations were detected (Figure 16). All varieties in Tattendorf showed higher capacitance values than in St. Andrä. Measurements of the wheat roots in Breitstetten were performed roughly one month later. The different plant growth stages as well as less precipitation before this measurement date resulted in strongly decreased

capacitance values. These values were in a range from 0.48 - 0.20 nF and were not displayed in Figure 16.

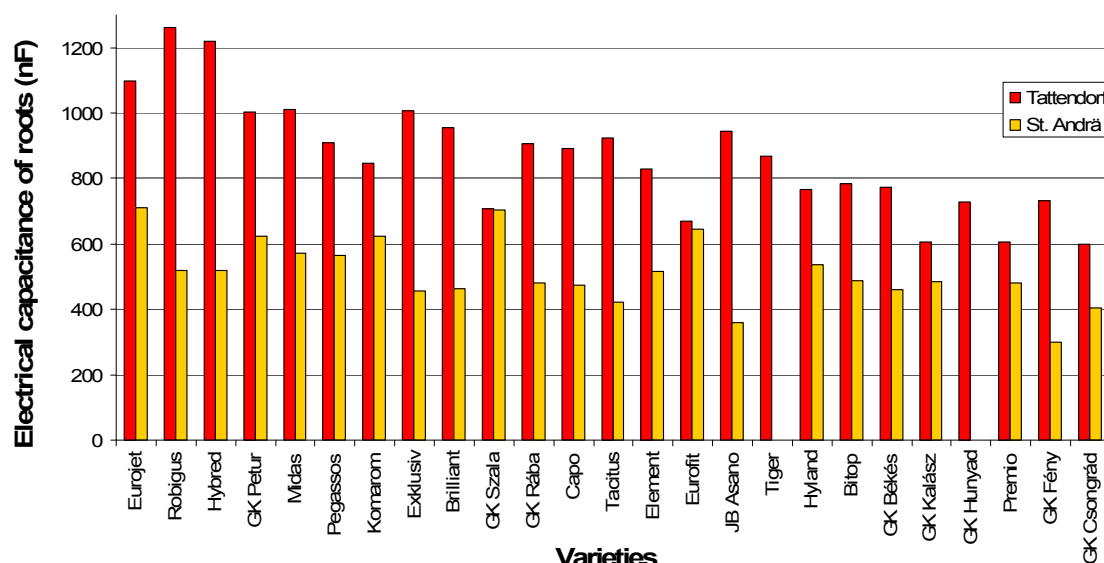


Figure 16: Electrical capacitance of roots of the 25 varieties in Tattendorf and St. Andrä (average of three replications, varieties arranged according to the average at all locations, capacitance values of the wheat roots in Breitstetten are not displayed because they were very low, no electrical capacitance measurement of Tiger and GK Hunyad in St. Andrä)

According to the analysis of variance the interaction between variety and location was little but significant at a level of $p \leq 0.05$ (Table 6).

Osmotic potential (OSP)

As expected, there were just slight differences between the varieties (Figure 17). Nevertheless these differences were significant (Table 6). The varieties GK Csongrád, Midas, Tiger, Element, GK Békés, Robigus and Tacitus showed the highest osmotic potential with ranges from -1.57 to -1.54 MPa.

The Austrian genotypes Bitop, Exklusiv and Komarom showed the lowest osmotic potential values (-1.76 to -1.75 MPa).

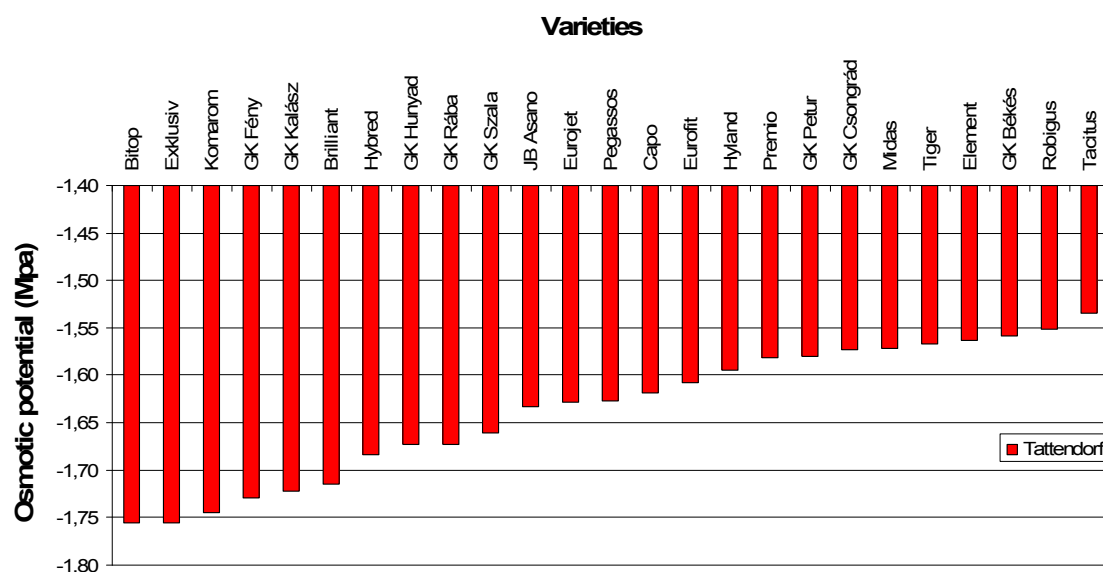


Figure 17: Flag leaf osmotic potential of the 25 varieties in Tattendorf

(average of three replications, no osmotic potential measurements were performed in Breitstetten and St. Andrä)

Flag leaf canopy temperature (OTE)

Significant differences (Table 6) concerning the flag leaf canopy temperature were noticed among the varieties. Capo, Komarom, Hyland, GK Petur and Robigus showed the highest canopy temperatures (Figure 18) with average values of 22.4 – 24.5°C. Eurofit, Exklusiv, Premio, GK Békés, GK Rába and Brilliant just reached temperatures below 19°C.

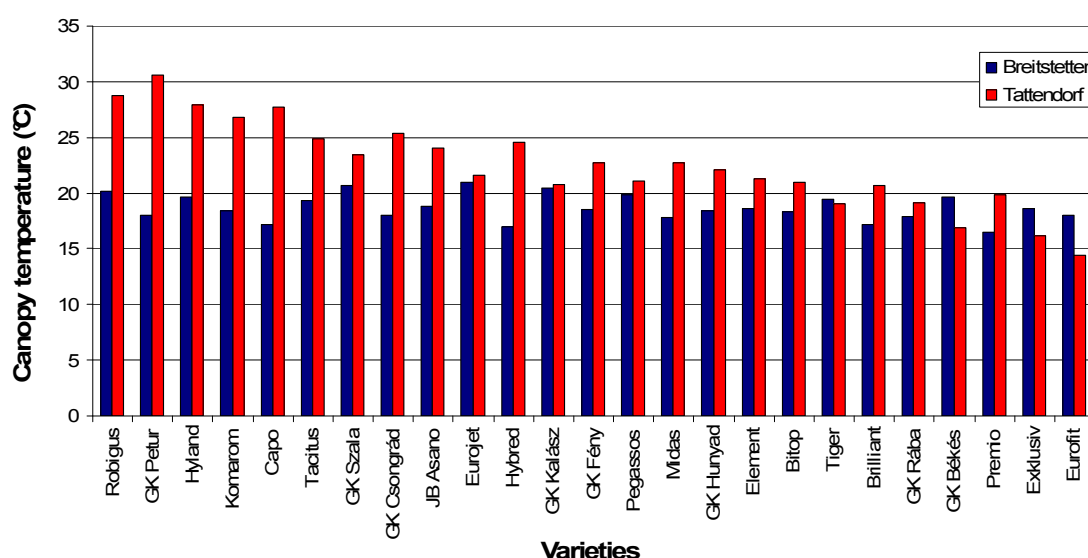


Figure 18: Flag leaf canopy temperature of the 25 varieties in Breitstetten and Tattendorf

(average of three replications, varieties arranged according to the average at all locations, no canopy temperature measurements were performed in St. Andrä)

The factor location induced significant variations regarding the canopy temperature (Table 6). Wheat plants in Tattendorf showed canopy temperatures between 14 - 30°C. In Breitstetten the temperature of the flag leaves was in the range from 16 - 20°C.

The interaction between variety and location was little but significant at a level of $p \leq 0.05$.

Flag leaf chlorophyll content (SPD)

Significant genotype variability was noticed for the chlorophyll content (Table 6). At all three locations the highest chlorophyll content was reached by the varieties Robigus, Brilliant, GK Szala, GK Kalász, GK Csongrád, Tacitus, Midas, Premio, GK Petur, GK Fény and GK Rába (Figure 19). SPAD units ranged from 48.3 - 52.8 on average.

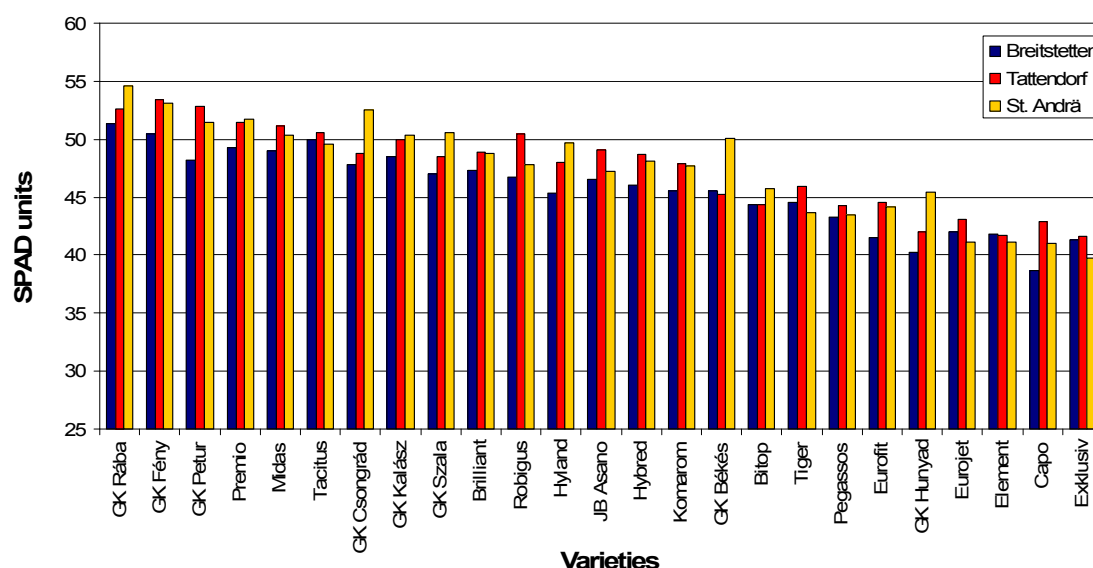


Figure 19: Flag leaf chlorophyll content of the 25 varieties in Breitstetten, Tattendorf and St. Andrä

(average of three replications, varieties arranged according to the average at all locations)

Exklusiv, Capo, Element, Eurojet, GK Hunyad, Eurofit and Pegassos had the lowest chlorophyll content on average at all locations. Capo and Exklusiv showed an average value of 40.9 units.

According to the analysis of variance the chlorophyll content showed significant variability among the locations (Table 6). The highest SPAD units were reached by the varieties in St. Andrä and Tattendorf. Wheat plants in Breitstetten had almost always the lowest chlorophyll content.

The interaction between variety and location was little but significant at a level of $p \leq 0.05$.

Stomatal conductance (STO)

The analysis of variance showed little but significant variability among the varieties for the stomatal conductance (Table 6). Robigus, GK Rába, Eurofit and GK Békés obtained the highest stomatal conductance ($515 - 545 \text{ mmol m}^{-2} \text{ s}^{-1}$) on average at the two locations (Tattendorf and Breitstetten). A conductance below $400 \text{ mmol m}^{-2} \text{ s}^{-1}$ was observed with Brilliant, GK Hunyad, Capo, GK Szala and GK Fény (Figure 20).

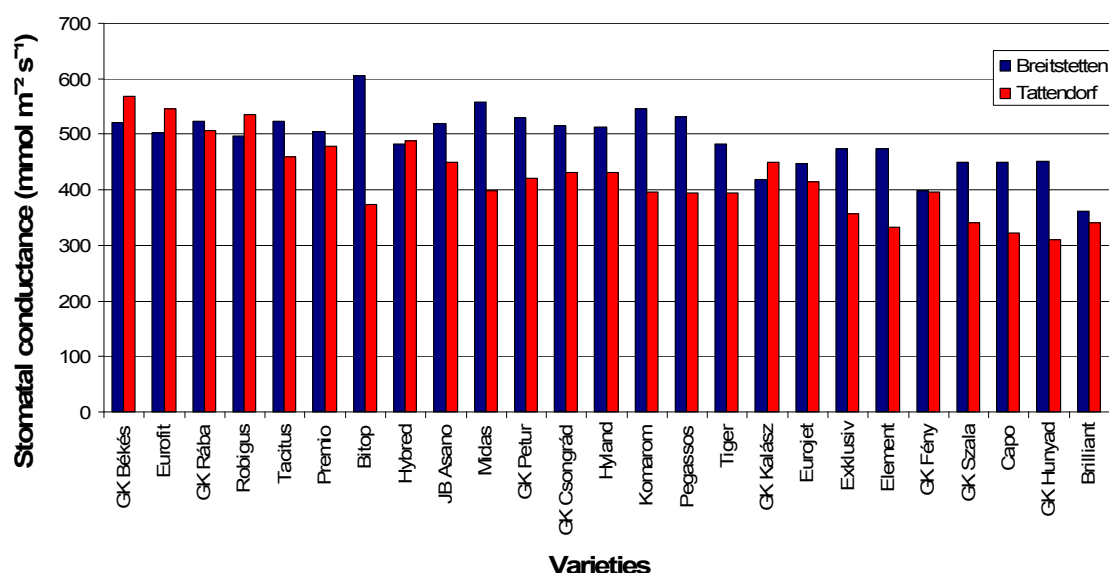


Figure 20: Flag leaf stomatal conductance of the 25 varieties in Breitstetten and Tattendorf (average of three replications, varieties arranged according to the average at all locations, no stomatal conductance measurements were performed in St. Andrä)

Among the locations significant differences were noticed (Table 6). The stomatal conductance of the flag leaves in Breitstetten was mostly higher than the flag leaf conductance values in Tattendorf.

The interaction between variety and location was non significant.

3.1.2. Stress indicators

In the core set as well as in the supplemental set significant genotype effects ($p \leq 0.05$) were shown in all stress indicators (Table 7 and Table A 2).

Large variations among the locations were noticed again for all stress indicators, namely for the leaf rolling and the leaf senescence scorings. In the additional 72 genotypes significant location differences were only detected for the second and third leaf senescence scoring. Significant interactions ($p \leq 0.05$) between the varieties and the locations were given for the leaf rolling, the first and the third leaf senescence scoring.

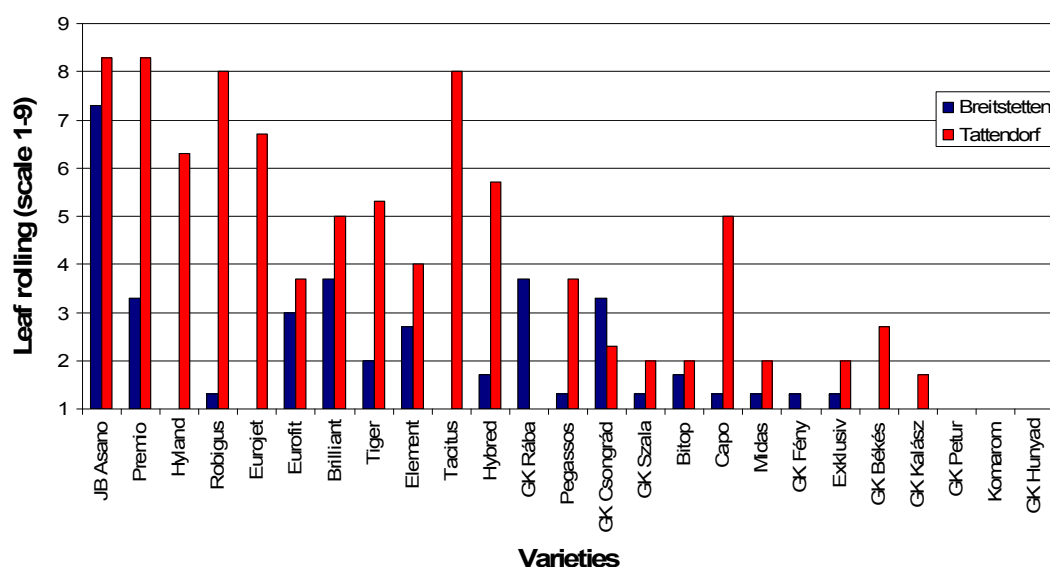
Table 7: Analysis of variance F values of the stress indicators

Factors	Dependent Variables							
	BLRO		SZF 1		SZF 2		SZF 3	
Variety	*	12.62	*	4.49	*	2.85	*	3.60
Location	*	103.68	*	19.91	*	109.39	*	81.10
Variety x Location	*	7.07	*	2.04		0.72	*	1.95

* = significant at a level of $p \leq 0.05$

Leaf rolling (BLRO)

According to the analysis of variance there were significant variations ($p \leq 0.05$) among the varieties for the leaf rolling (Table 7). The varieties GK Hunyad, Komarom and GK Petur (Figure 21) did not show a sign of leaf rolling (scale number 1) at any of the locations. Some other Hungarian genotypes (GK Kalász, GK Békés and GK Fény) as well as two Austrian ones (Exklusiv and Midas) followed with an average leaf rolling scale of 1.2 - 1.9 at both locations. Leaves of the German varieties Robigus, Hyland, Premio and JB Asano tended to roll more. An average scale of 4.1 - 7.8 was achieved.

**Figure 21: Leaf rolling of the 25 varieties in Breitstetten and Tattendorf**

(average of three replications, varieties arranged according to the average at all locations, no rating of leaf rolling in St. Andrä, 1 = no leaf rolling, 9 = intense leaf rolling)

Significant differences among the locations were shown for the leaf rolling (Table 7). Leaves of the varieties in Tattendorf tended to roll more than in Breitstetten. In Tattendorf the leaf

rolling scale ranged from 1 - 8.3. Almost none of the varieties in Breitstetten reached the leaf rolling scale of 4, except JB Asano.

The interaction between variety and location was significant at a level of $p \leq 0.05$.

Leaf senescence (SZF 1-3)

At all three scoring dates the varieties showed significant differences for the leaf senescence (Table 7).

At the first screening date the flag leaf senescence Robigus, Hybred, Eurojet, Eurofit, Pegassos, JB Asano, Brilliant, Midas and Tiger showed a low senescence rate. These varieties stayed under ten percent on average at all locations. The flag leaves of the varieties Element, Komarom and most of the Hungarian ones (GK Békés, GK Kalász, GK Fény, GK Szala, GK Hunyad, GK Petur and GK Csongrád) reached on average between 20 – 40 % senescence (Figure 22).

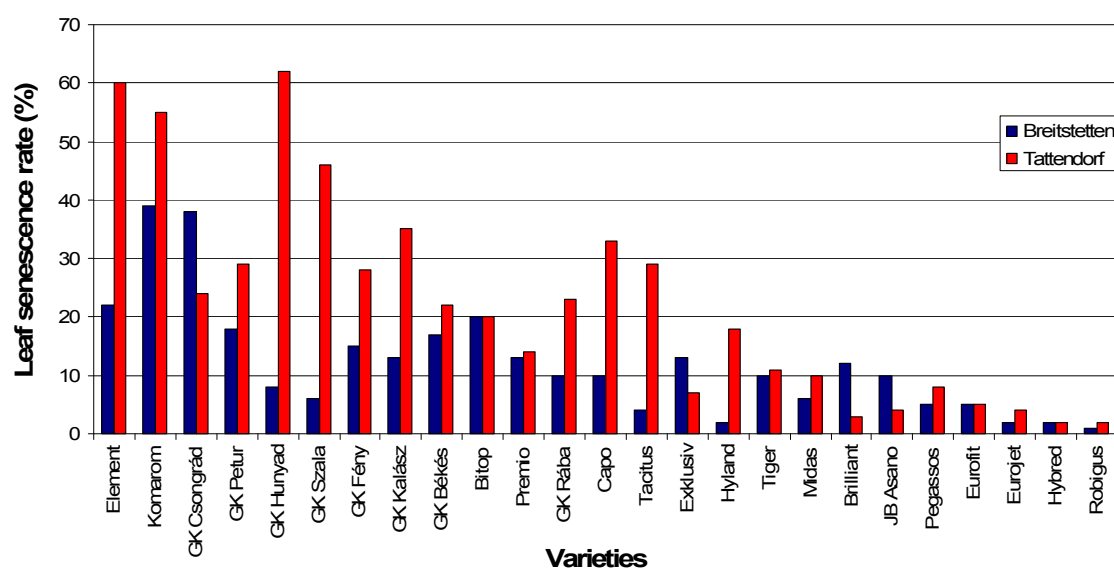


Figure 22: First leaf senescence scoring of the 25 varieties in Breitstetten and Tattendorf (average of three replications, varieties arranged according to the average at all locations, no rating of leaf senescence in St. Andrä)

The second and third scoring resulted in similar arrangements of the varieties Tiger, JB Asano, Midas, Eurofit, Eurojet, Pegassos, Brilliant, Hybred and Robigus. At the second screening these genotypes showed senescence rates from 20 – 65 % on average (Figure 23). 45 – 86 % leaf senescence was scored at the third scoring (Figure 24).

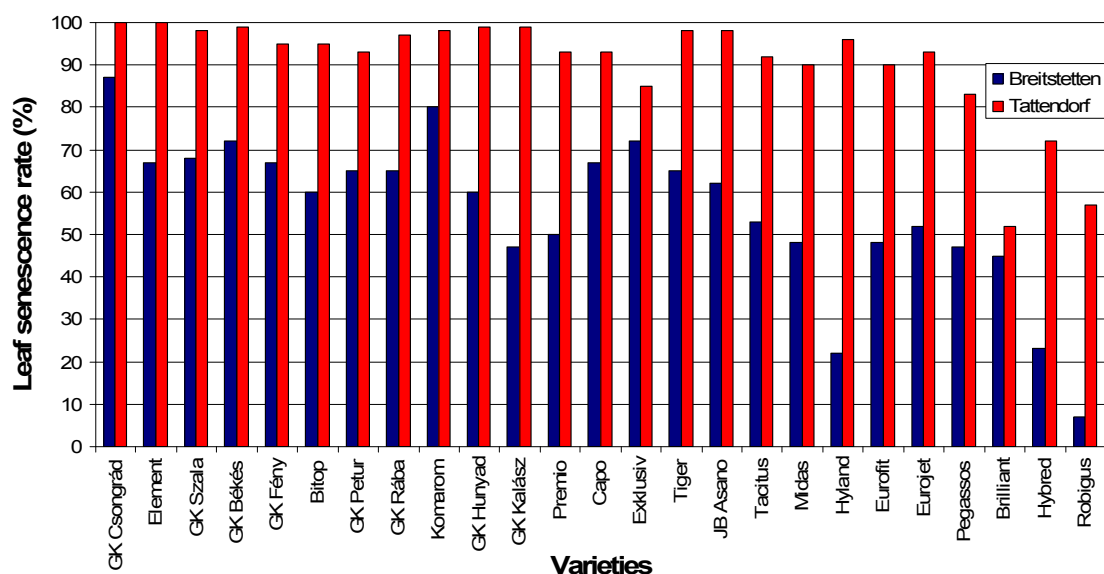


Figure 23: Second leaf senescence scoring of the 25 varieties in Breitstetten and Tattendorf (average of three replications, varieties arranged according to the average at all locations, no rating of leaf senescence in St. Andrä)

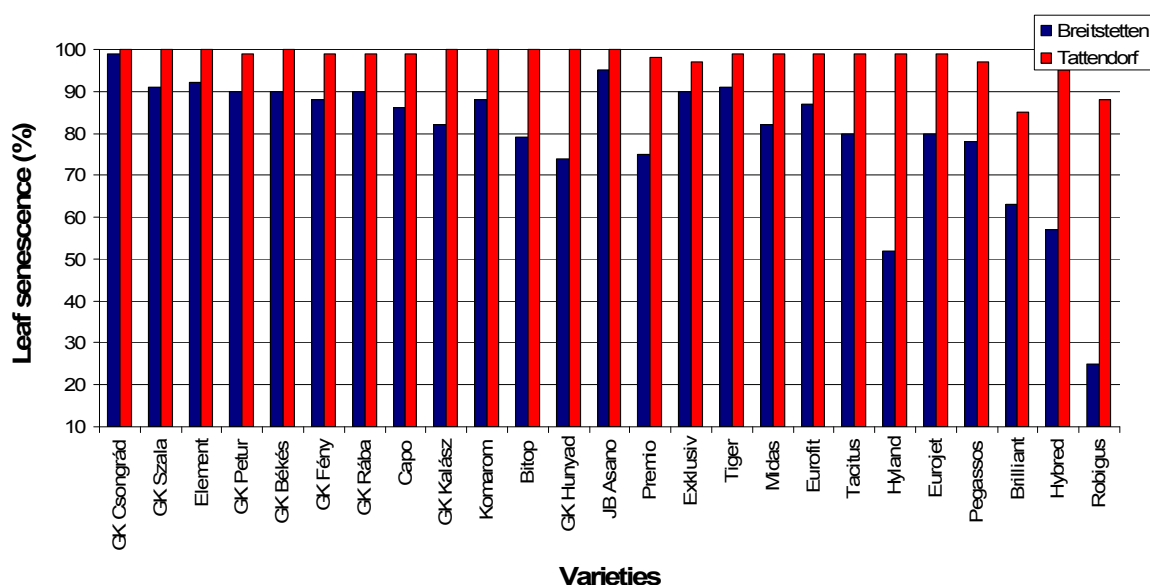


Figure 24: Third leaf senescence scoring of the 25 varieties in Breitstetten and Tattendorf (average of three replications, varieties arranged according to the average at all locations, no rating of leaf senescence in St. Andrä)

The varieties Robigus and Hybred were remarkable because they ranked last at all three screening times. Robigus barely reached the 50 percent mark on average at all locations and Hybred hit the 60 percent mark.

Large variations among the locations were detected for the leaf senescence (Table 7). At all three scorings, wheat leaves in Tattendorf showed a higher senescence rate than in Breitstetten.

Significant interactions ($p \leq 0.05$) between the varieties and the locations were given for the first and the third screening date. This significance was not only shown in the core set but also in the supplemental set (Table A 2).

3.2. Agronomic traits

3.2.1. Growth stages and plant morphology

Regarding the growth stages the analysis of variance revealed significant variations among the varieties, the locations and the interaction between varieties and locations (Table 8 and Table A 3). The factors variety and location showed significant differences for the plant height too. The interactions between varieties and locations were not significant at a level of $p \leq 0.05$.

Table 8: Analysis of variance F values of the growth stages and the plant morphology

Factors	Dependent Variables							
	DTAE		DTBL		DTGR		WHOE	
Variety	*	99.59	*	118.12	*	23.17	*	40.10
Location	*	3102.54	*	7219.96	*	1621.80	*	121.97
Variety x Location	*	4.76	*	8.15	*	3.17		1.15

* = significant at a level of $p \leq 0.05$

Growth stages (DTAE, DTBL, DTGR)

Significant genotype variability was shown for the growth stages. On average across all locations, the Hungarian varieties GK Csongrád, GK Kalász, GK Fény and GK Békés were the first who reached the heading stage (DTAE), starting on 22nd of May (Figure 25). Two Austrian varieties, namely Tacitus and Element were also among the early maturing genotypes, with average heading dates of 27th of May. The varieties which reached the heading stage the latest (on 3rd of June) were German ones (Brilliant, Pegassos, Robigus and Hybred) and Eurojet.

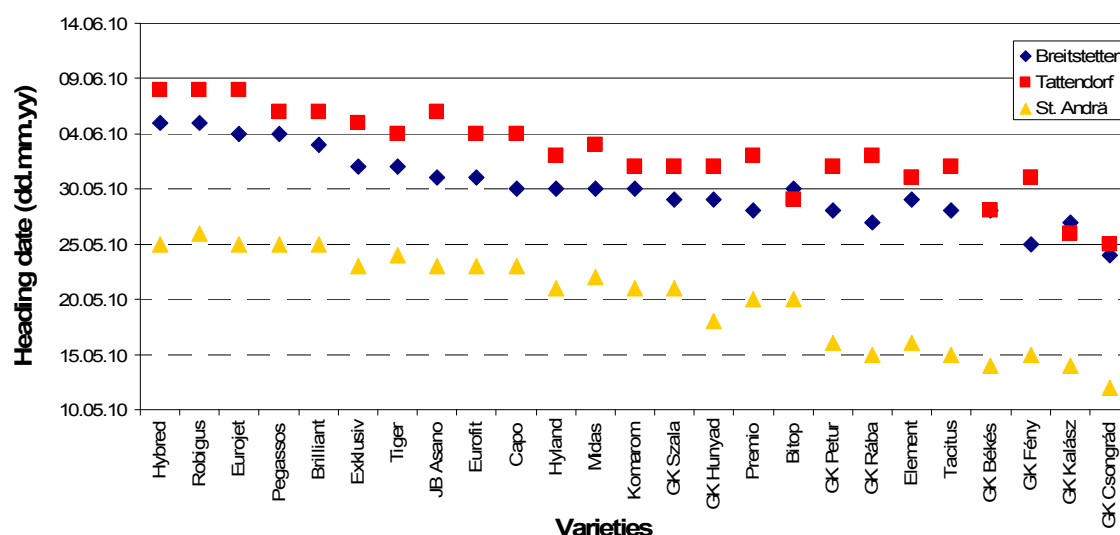


Figure 25: Heading date of the 25 varieties in Breitstetten, Tattendorf and St. Andrä
(average of three replications, varieties arranged according to the average at all locations)

Also the flowering stage (DTBL) occurred first by Hungarian varieties (GK Csongrád, GK Kalász, GK Rába, GK Fény and GK Petur), starting on the 29th of May, on average (Figure 26). Tacitus, Element and Bitop (Austrian varieties) were once again the early flowering varieties too. At all locations the latest genotypes concerning the flowering stage were Hybred, Brilliant, Pegassos, Eurojet, JB Asano and Robigus. The average flowering date was reached by these varieties on the 8th and 9th of June.

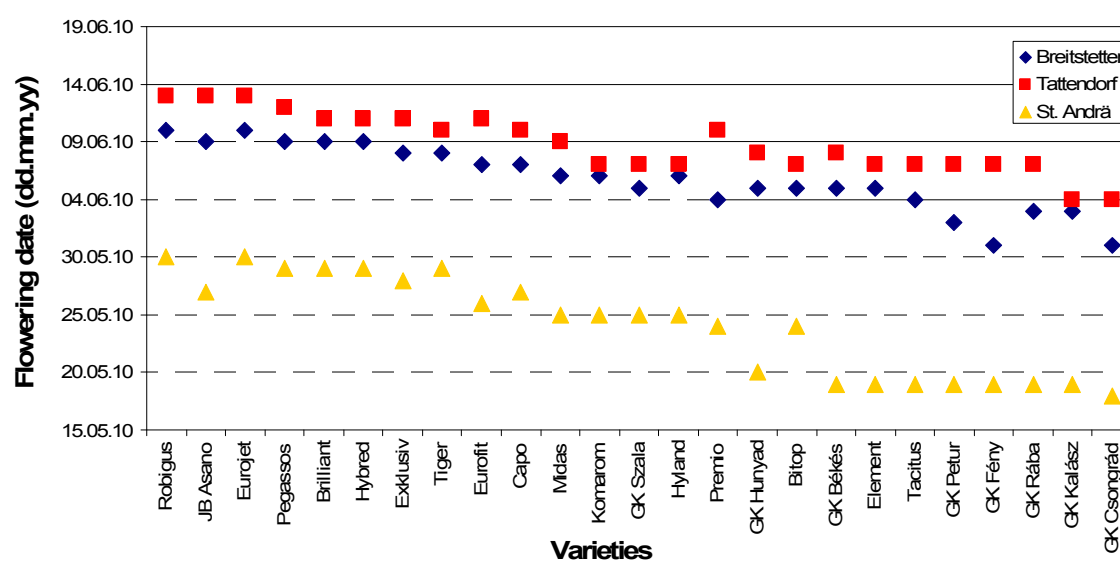


Figure 26: Flowering date of the 25 varieties in Breitstetten, Tattendorf and St. Andrä
(average of three replications, varieties arranged according to the average at all locations)

At all locations the Hungarian varieties GK Csongrád, GK Rába, GK Fény, GK Petur, GK Békés and GK Kalász as well as the Austrian varieties Tacitus, Bitop and Komarom represented again the group of early maturing genotypes (Figure 27). The average grain maturity date (DTGR) started at the 8th of July. The genotypes that reached the physiological grain maturity last were Eurofit, Tiger, Brilliant, Pegassos, Eurojet, Hybred and Robigus, showing an average maturity date between the 12th and the 15th of July.

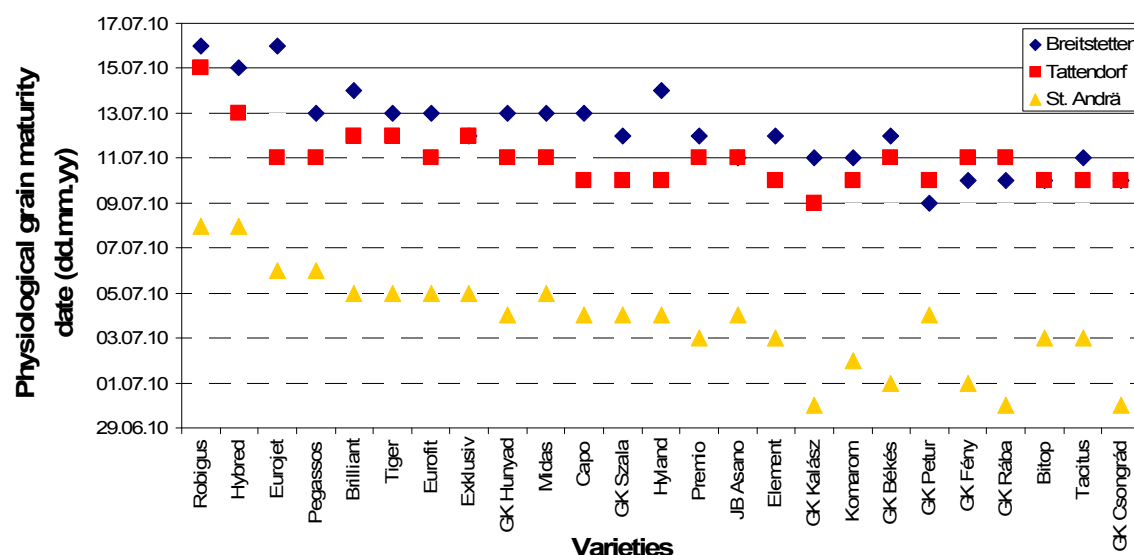


Figure 27: Date of physiological grain maturity of the 25 varieties in Breitstetten, Tattendorf and St. Andrä

(average of three replications, varieties arranged according to the average at all locations)

Related to the growth stages large and significant variations among the locations were noticed (Table 8). Wheat plants in St. Andrä reached the heading stage as well as the flowering and physiological grain maturity stage first (Figure 25, Figure 26 and Figure 27). The growth stages started 7 to 18 days earlier than at the other two locations. Varieties in Tattendorf reached the growth stages 10 to 16 days later than comparatively in St. Andrä. Regarding the heading and flowering stages, genotypes in Breitstetten were the median of those in St. Andrä and Tattendorf. Only at the physiological grain maturity stage the varieties in Breitstetten were the last ones reaching it (Figure 27).

According to the analysis of variance the interaction between variety and location was little but significant at a level of $p \leq 0.05$ (Table 8).

Plant morphology

Variety differences were established for the plant height (WHOE) (Table 8). At all locations Element, Eurofit, Eurojet, Capo and Tiger were the tallest varieties (Figure 28). They reached

average plant heights of 97 – 101 cm. The shortest varieties were Premio, Robigus, GK Kalász, GK Csongrád, GK Petur and GK Békés. The average plant height of these shortest varieties at all locations ranged from 71 – 78 cm.

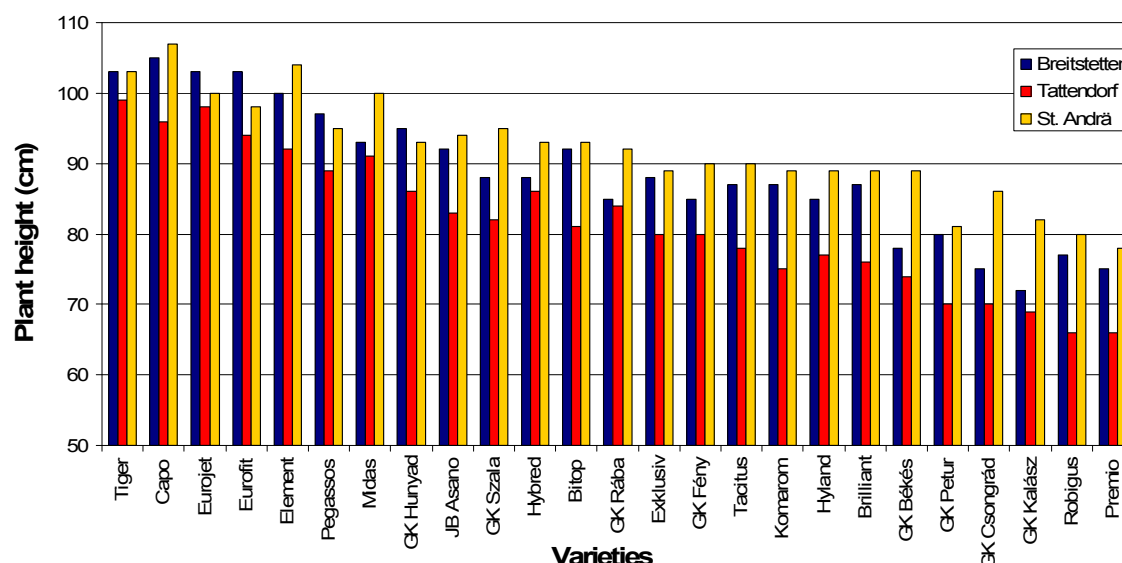


Figure 28: Plant height of the 25 varieties in Breitstetten, Tattendorf and St. Andrä
(average of three replications, varieties arranged according to the average at all locations)

Large variations were noticed among the locations (Table 8) too. Wheat plants in Breitstetten and St. Andrä reached a plant height over 100 cm, whereas in Tattendorf these tallest cultivars only reached 90 – 99 cm.

The interaction between variety and location was non significant.

3.2.2. Yield and quality parameters

Significant genotype variability ($p \leq 0.05$) was shown on all yield variables in the core set (Table 9). In the supplemental set significant variations among the varieties were just noticed on the grain yield (Table A 4). The same tendency was realized for the variations among the locations.

In the core set large differences among the locations were again detected for all yield variables. No interactions between the varieties and the locations were calculated for the grain yield, the thousand grain weight, the test weight and the grain protein content.

Table 9: Analysis of variance F values of the yield and the quality parameters

Factors	Dependent variables									
	BEST		KOEQ		TKGN		HLGW		RPRT	
Variety	*	4.57	*	6.23	*	12.16	*	13.42	*	5.15
Location	*	94.98	*	314.52	*	48.82	*	65.61	*	138.09
Variety x Location		1.17		---		---		---		---

* = significant at a level of $p \leq 0.05$

Ear density (BEST)

Among the varieties significant variations were noticed for the ear density (Table 9). Pegassos, Hyland, Hybred, GK Csongrád, Komarom and Robigus showed the highest ear density (Figure 29) with over 500 ears m^{-2} on average. The varieties Tiger, Bitop, Midas, Element, JB Asano and Capo had the lowest amount of ears m^{-2} . Average values below 420 ears m^{-2} were reached.

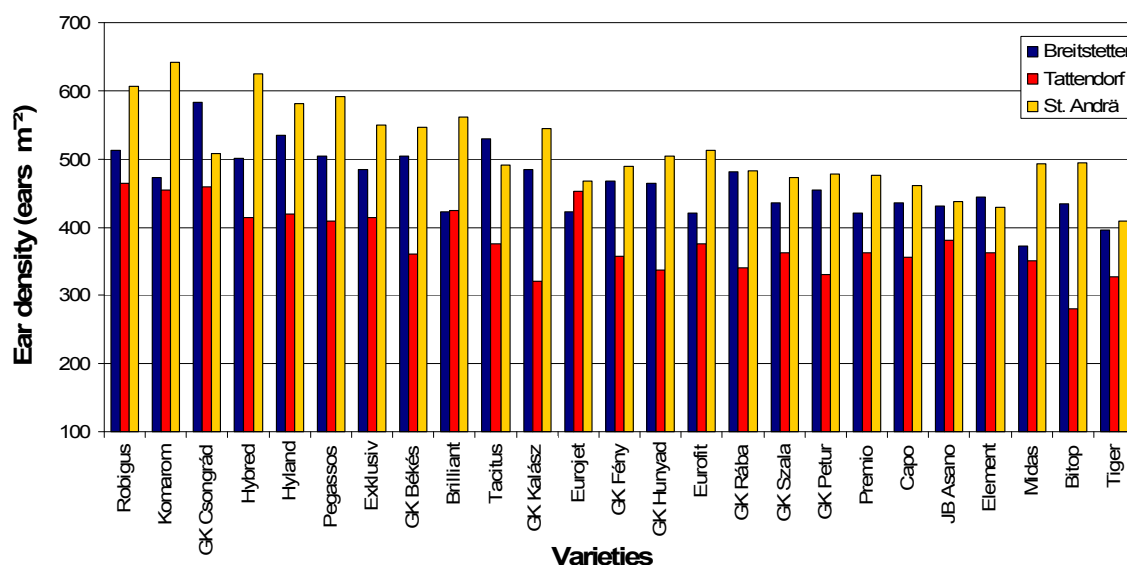


Figure 29: Ear density of the 25 varieties in Breitstetten, Tattendorf and St. Andrä
(average of three replications, varieties arranged according to the average at all locations)

According to the analysis of variance (Table 9) large differences among the locations were noticed. Wheat plants in Tattendorf did not grow densely showing ranges from 280 - 470 ears m^{-2} . The opposite was detected in St. Andrä, where wheat varieties reached tiller densities between 400 - 650 ears m^{-2} .

No significant interaction ($p \leq 0.05$) between variety and location was found for the ear density.

Grain yield (KOEQ)

Significant genotype variability was noticed for the grain yield (Table 9). The highest grain yield (83 dt ha^{-1} on average at all locations) was reached by the hybrid variety Hyland (Figure 30).

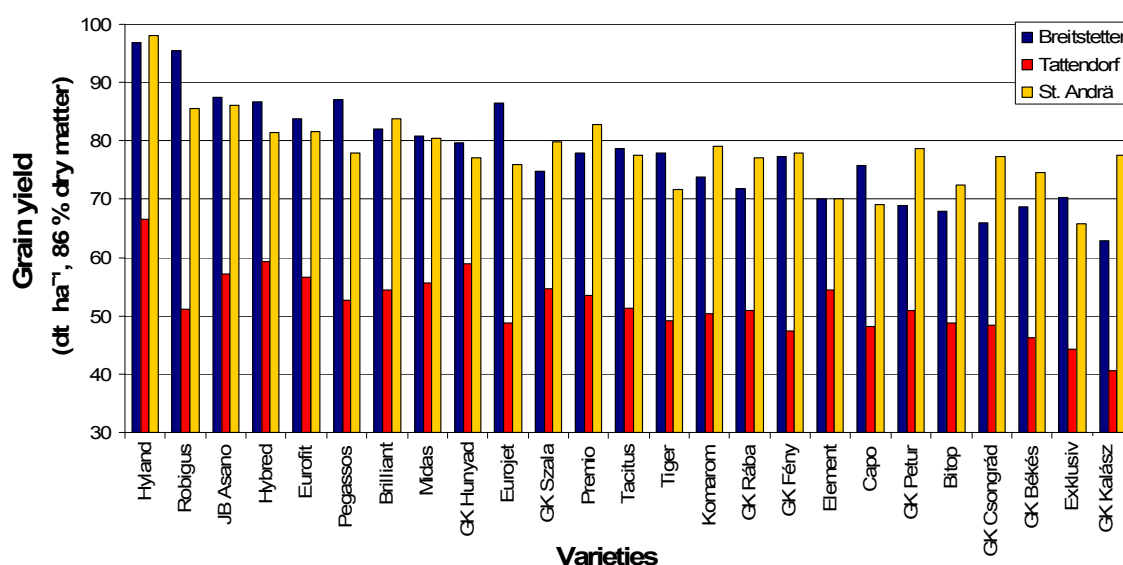


Figure 30: Grain yield of the 25 varieties in Breitstetten, Tattendorf and St. Andrä
(average of three replications, varieties arranged according to the average at all locations)

Comparable grain yields were found for Brilliant, Pegassos, Eurofit, Hybred, JB Asano and Robigus with ranges from $70 - 77 \text{ dt ha}^{-1}$. GK Kalász, Exklusiv, GK Békés and GK Csongrád yielded poorly with average yields between $54 - 59 \text{ dt ha}^{-1}$.

As illustrated in Figure 30 large variations among locations were shown for the grain yield. The highest yields were achieved by the wheat genotypes in St. Andrä and in Breitstetten. In Tattendorf the varieties obtained only poor yields.

Thousand grain weight (TKGN)

According to the analysis of variance significant differences among the varieties were shown (Table 9). Average weight ranged from $35 - 50 \text{ g}$. The highest grain weight was reached by the varieties GK Szala, Tiger, Eurojet and GK Hunyad (Figure 31) having an average thousand grain weight of $49 - 50 \text{ g}$.

The genotypes with the lowest thousand grain weight (below 40 g) were Robigus, GK Csongrád and Brilliant.

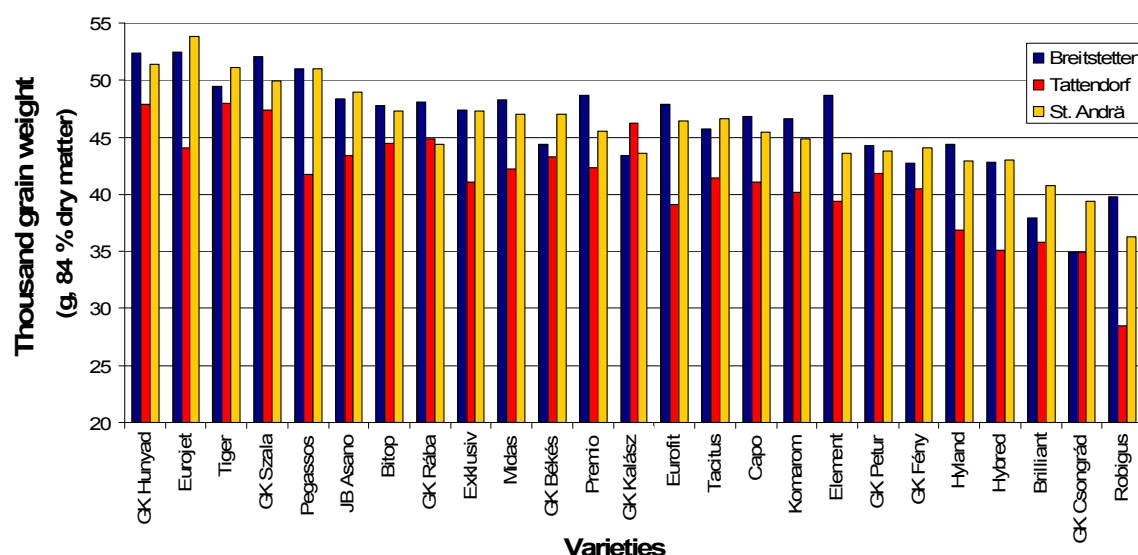


Figure 31: Thousand grain weight of the 25 varieties in Breitstetten, Tattendorf and St. Andrä (varieties arranged according to the average at all locations)

Significant variability was noticed among the locations, so varieties in St. Andrä and Breitstetten reached the highest thousand grain weight (35 – 54 g) whereas genotypes in Tattendorf showed the lowest (28 – 48 g).

Test weight (HLGW)

As already mentioned in chapter 3.2.2 significant differences among the varieties were detected. An average test weight over 83 kg was reached by the genotypes GK Hunyad, Element, GK Fény, Capo, Bitop and Midas (Figure 32). The lowest test weight (below 80 kg) was achieved by the varieties Robigus, Hybred, GK Petur, Premio and Hyland.

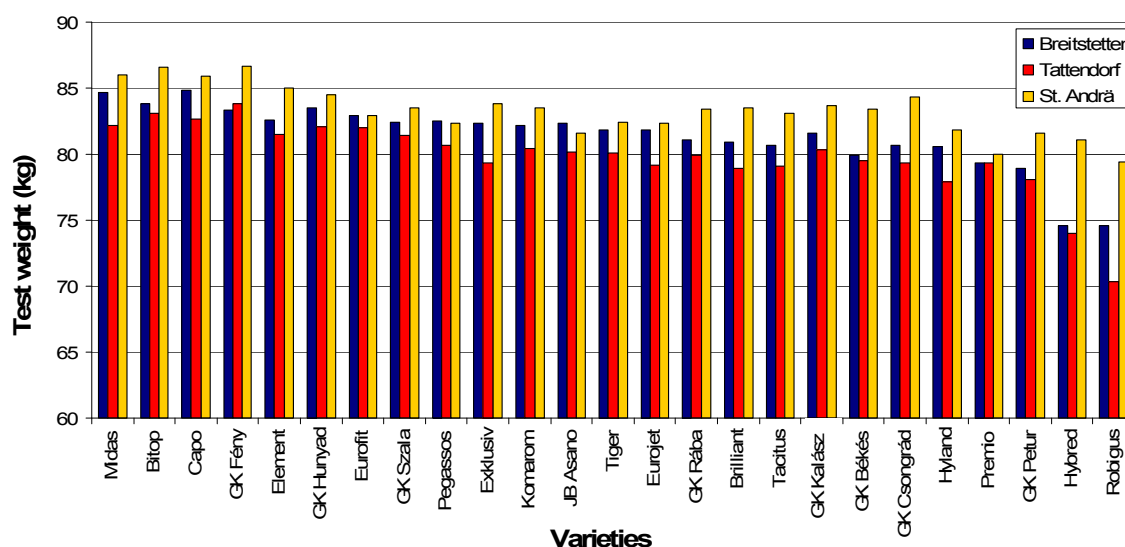


Figure 32: Test weight of the 25 varieties in Breitstetten, Tattendorf and St. Andrä (varieties arranged according to the average at all locations)

Little but significant location variations were noticed for the test weight. Wheat crops in St. Andrä and in Breitstetten reached the highest test weight. Genotypes in Tattendorf hardly showed test weights above 82 kg on average.

Grain protein content (RPRT)

Significant genotype variability was detected for the grain protein content (Table 9). Bitop, GK Békés, Komarom and Exklusiv reached protein contents above 16 % on average (Figure 33). German varieties (Hyland, Robigus, Hybred, JB Asano and Premio) showed the lowest protein content with an average range from 13 – 14 %.

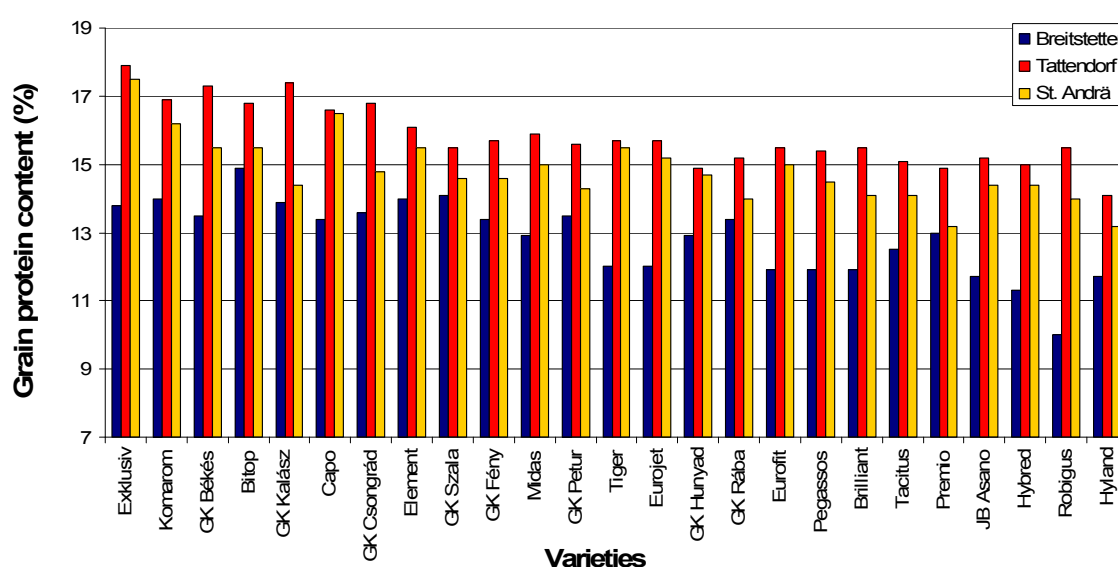


Figure 33: Grain protein content of the 25 varieties in Breitstetten, Tattendorf and St. Andrä (varieties arranged according to the average at all locations)

As shown in Figure 33 and Table 9 location based differences were noticed. The highest protein content was reached by varieties in Tattendorf. Wheat grains in St. Andrä showed protein content ranges from 13 - 17.5 % comparable with the protein contents in Tattendorf. Genotypes in Breitstetten just reached protein contents between 10 – 15 % and were therefore the crops with the lowest grain protein contents.

3.3. Correlations

Based on the analysis of variance and due to the big variations among the locations correlations were calculated separately for the locations. Only selected figures are shown.

3.3.1. Correlations among the novel selection criteria

In the core set there were no correlations noticed between the electrical capacitance of roots and the other novel traits (osmotic potential, canopy temperature, chlorophyll content and stomatal conductance) (Table 10). A positive tendency between the electrical capacitance and the canopy temperature was supported by a highly significant positive correlation ($p \leq 0.01$) in the supplemental set. Another positive correlation was shown between the electrical capacitance and the stomatal conductance, again just in the additional 72 genotypes.

Table 10: Correlation coefficients among the novel selection criteria (core set on the left and supplemental set on the right)

		EKA	OSP	OTE	SPD	STO			EKA	OSP	OTE	SPD	STO
EKA	Bre			.000	.263	-.193	EKA	Bre			-.058	-.091	-.125
	Tat	/	.112	.333	-.016	.086		Tat	/		.319**	.131	.353**
	St. A				-.168			St. A					
OSP	Bre						OSP	Bre					
	Tat		/	.236	.064	.327		Tat		/			
	St. A							St. A					
OTE	Bre				-.128	-.039	OTE	Bre				-.053	.051
	Tat			/	.349	-.173		Tat			/	.175	.245*
	St. A							St. A					
SPD	Bre					.164	SPD	Bre					.291*
	Tat				/	.394		Tat				/	.249*
	St. A							St. A					
STO	Bre						STO	Bre					
	Tat					/		Tat					/
	St. A							St. A					

* = significant at the level $p \leq 0.05$

** = significant at the level $p \leq 0.01$

The osmotic potential showed a positive correlation tendency to the other observed traits in the core set. No significance was indicated (Table 10).

In the core set there was a negative tendency between the canopy temperature and the stomatal conductance, but no significant one. In the additional 72 genotypes, conversely, there was a positive correlation ($p \leq 0.05$).

Between the chlorophyll content and the stomatal conductance a positive tendency was noticed in the core set. This assumption was again confirmed by the 72 genotypes ($p \leq 0.05$) (Figure 34).

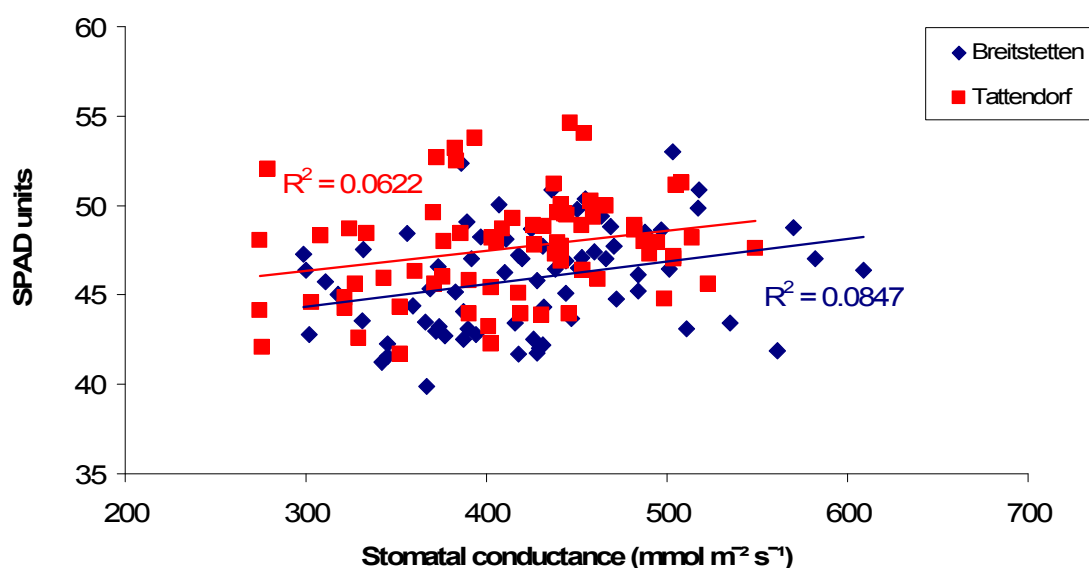


Figure 34: Intervarietal correlation between the stomatal conductance and the chlorophyll content (SPAD units) of the additional 72 genotypes (no measuring of the stomatal conductance in St. Andrä)

3.3.2. Novel selection criteria correlated with the stress indicators

As shown in Figure 35 a negative correlation ($p \leq 0.05$ and $p \leq 0.01$) was noticed between the electrical capacitance and the three leaf senescence scores. The same reaction was shown in the supplemental set (Table 11) too.

Table 11: Correlation coefficients between the novel selection criteria and the stress indicators (core set on the left and supplemental set on the right)

		BLRO	SZF1	SZF2	SZF3
EKA	Bre	-.052	.066	.096	.037
	Tat	.266	-.432*	-.639**	-.517**
	St. A				
OSP	Bre				
	Tat	.507**	-.080	.094	.033
	St. A				
OTE	Bre	-.459*	-.151	-.123	-.145
	Tat	.129	.171	-.206	-.128
	St. A				
SPD	Bre	.129	.121	-.043	-.049
	Tat	-.044	-.127	-.097	-.187
	St. A				
STO	Bre	.004	.337	.176	.142
	Tat	.273	-.413*	-.072	-.080
	St. A				

		BLRO	SZF1	SZF2	SZF3
EKA	Bre	-.017	-.014	.070	.169
	Tat	-.105	-.571**	-.469**	-.479**
	St. A				
OSP	Bre				
	Tat				
	St. A				
OTE	Bre	.155	-.042	.009	-.100
	Tat	-.156	-.120	-.120	-.039
	St. A				
SPD	Bre	.015	.016	-.247*	-.258*
	Tat	-.181	-.019	-.117	-.094
	St. A				
STO	Bre	-.062	.095	-.117	-.169
	Tat	-.022	-.126	-.195	-.204
	St. A				

* = significant at the level $p \leq 0.05$

** = significant at the level $p \leq 0.01$

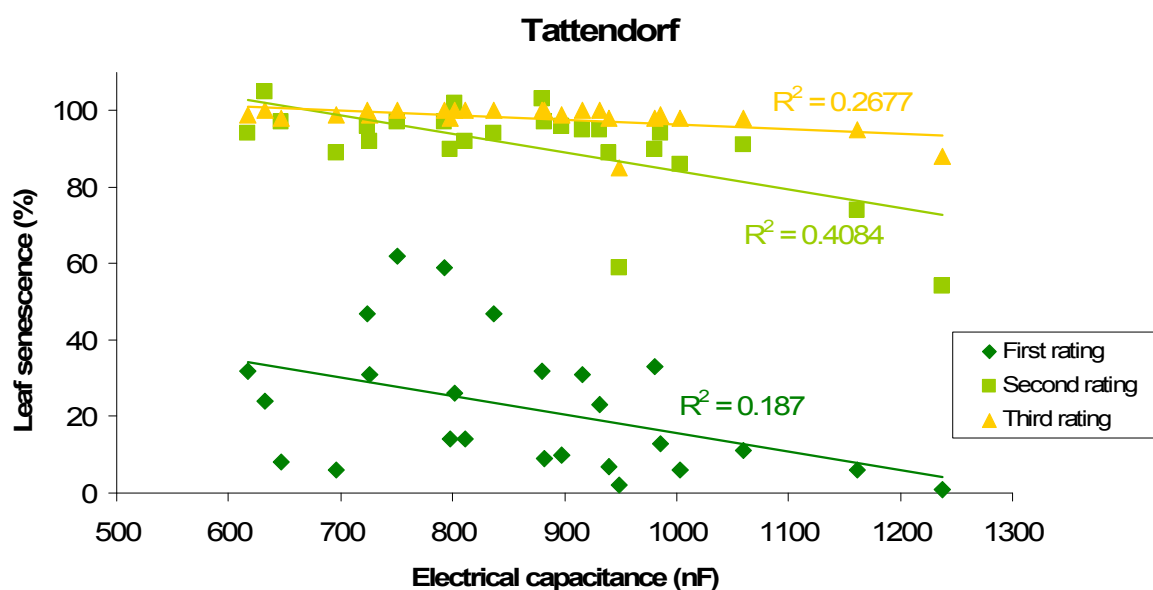


Figure 35: Interviarietal correlation between the electrical capacitance and the three leaf senescence scoring dates of the core set

(the capacitance values represent the data of the wheat roots in Tattendorf, values of the wheat roots in Breitstetten are not displayed because they were very low, no rating of leaf senescence in St. Andrä)

The osmotic potential showed a positive correlation ($p \leq 0.01$) only with the leaf rolling in the core set (Figure 36).

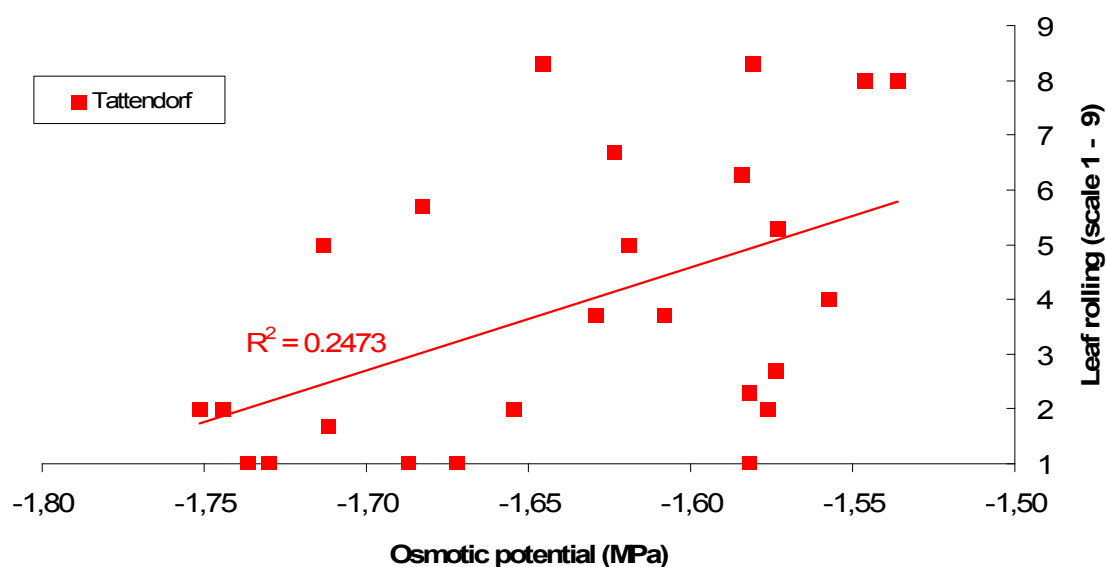


Figure 36: Interviarietal correlation between the osmotic potential and the leaf rolling of the core set

(the values represent the scorings and measurements in Tattendorf, for no other location the osmotic potential was measured, the comma represents the decimal place)

A negative correlation ($p \leq 0.05$) was found between the canopy temperature and the leaf rolling but just in the core set (Table 11 and Figure 37). No other correlations were found between the canopy temperature and the stress indicators.

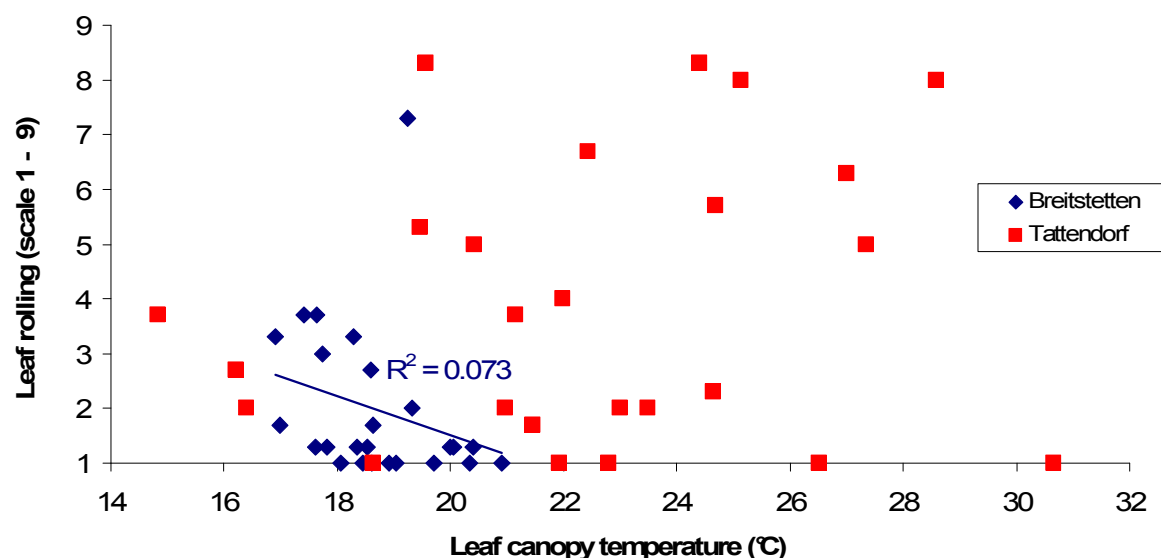


Figure 37: Intervarietal correlation between the leaf canopy temperature and the leaf rolling of the core set
(no measurements and ratings were performed in St. Andrä)

In the core set there was no significant correlation shown between the chlorophyll content and the stress indicators. Nevertheless a slight negative tendency was noticed between the SPAD units and the leaf senescence. This was underlined in the supplemental set with a negative correlation ($p \leq 0.05$) at the second and third scoring date (Table 11).

Concerning the stomatal conductance and the first scoring of leaf senescence a negative correlation ($p \leq 0.05$) was found but only in the core set (Table 11).

3.3.3. Novel selection criteria correlated with the growth stages and the plant morphology

The core set as well as the supplemental set showed almost the same correlations between the novel selection criteria, the growth stages and the plant morphology (Table 12).

Table 12: Correlation coefficients between the novel selection criteria, the growth stages and the plant morphology (core set on the left and supplemental set on the right)

		DTAE	DTBL	DTGR	WHOE
EKA	Bre	-.193	-.274	-.268	-.235
	Tat	.763**	.641**	.693**	.095
	St. A	.165	.123	.257	.232
OSP	Bre				
	Tat	.040	.091	.083	.018
	St. A				
OTE	Bre	.169	.211	.200	.021
	Tat	.077	-.113	-.044	-.251
	St. A				
SPD	Bre	-.402*	-.493*	-.407*	-.669**
	Tat	-.130	-.259	.048	-.546**
	St. A	-.537**	-.527**	-.499*	-.591**
STO	Bre	-.140	-.125	-.372	-.065
	Tat	.014	.118	.309	-.367
	St. A				

		DTAE	DTBL	DTGR	WHOE
EKA	Bre	.096	.073	.071	-.010
	Tat	.491**	.508**	.388**	-.072
	St. A				
OSP	Bre				
	Tat				
	St. A				
OTE	Bre	-.242*	-.200	-.164	.184
	Tat	.014	-.016	-.032	-.260*
	St. A				
SPD	Bre	-.308**	-.318**	-.163	-.543**
	Tat	-.046	-.022	.211	-.335**
	St. A	-.161	-.200	.011	-.320**
STO	Bre	-.092	-.108	-.077	-.228
	Tat	.045	.065	.125	-.482**
	St. A				

* = significant at the level $p \leq 0.05$

** = significant at the level $p \leq 0.01$

The electrical capacitance was positively correlated ($p \leq 0.01$) with the date of heading (Figure 38), anthesis and physiological grain maturity.

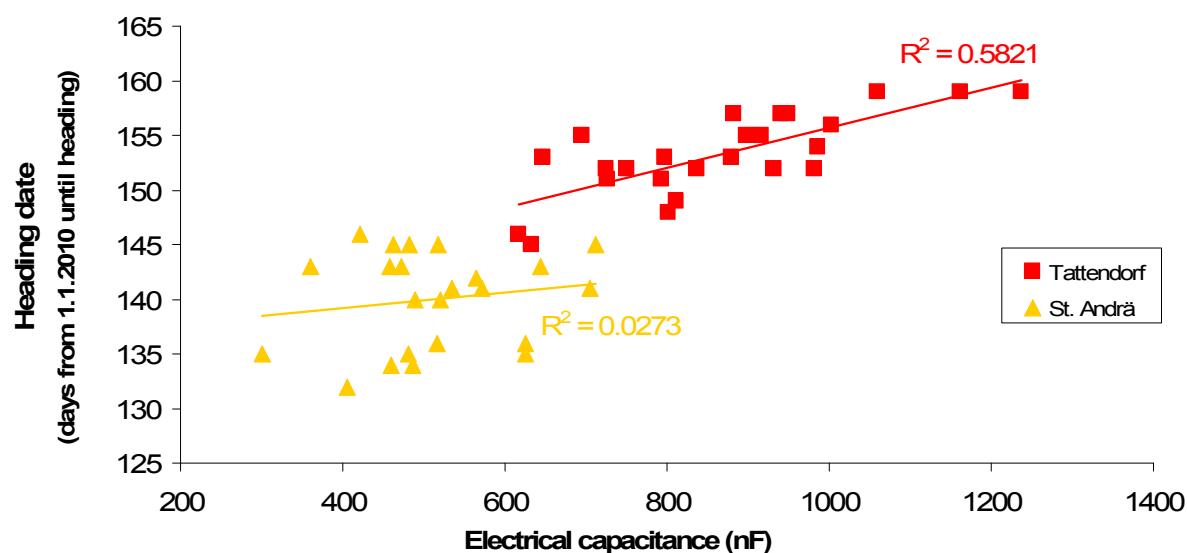


Figure 38: Intervarietal correlation between the electrical capacitance and the heading date of the core set

(capacitance values and their interactions in Breitstetten are not shown because capacitance values of the wheat roots were very low)

No significant correlation was found between the osmotic potential and the growth stages or the plant height.

In the supplemental set the canopy temperature showed negative correlations ($p \leq 0.05$) with the heading date and the plant height (Table 12).

As illustrated in Figure 39 and Figure 40 the chlorophyll content was negatively correlated ($p \leq 0.05$ and $p \leq 0.01$) with the growth stages and the plant height.

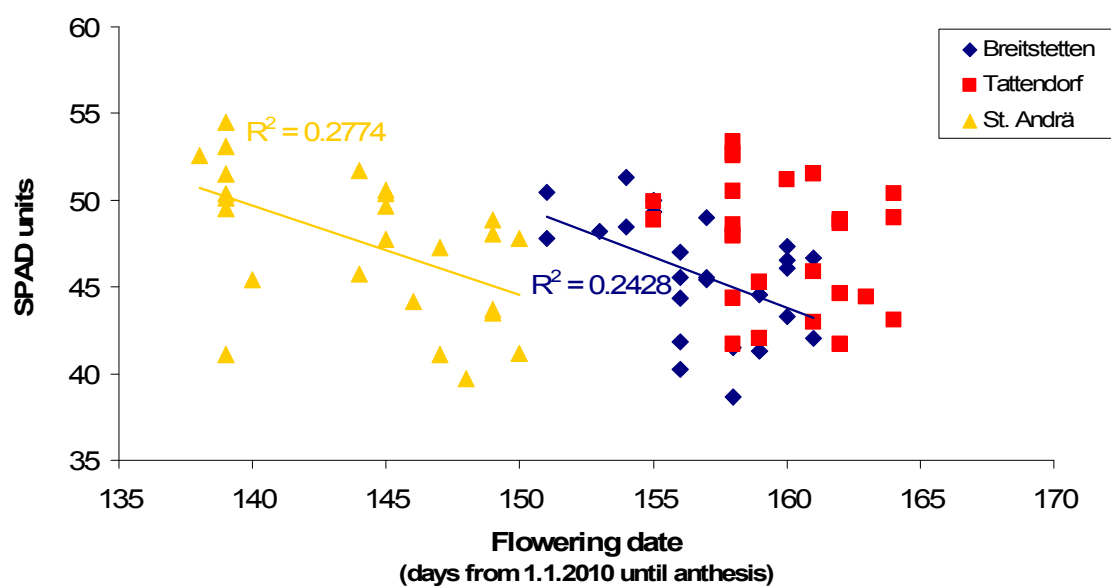


Figure 39: Intervarietal correlation between the flowering date and the chlorophyll content of the core set

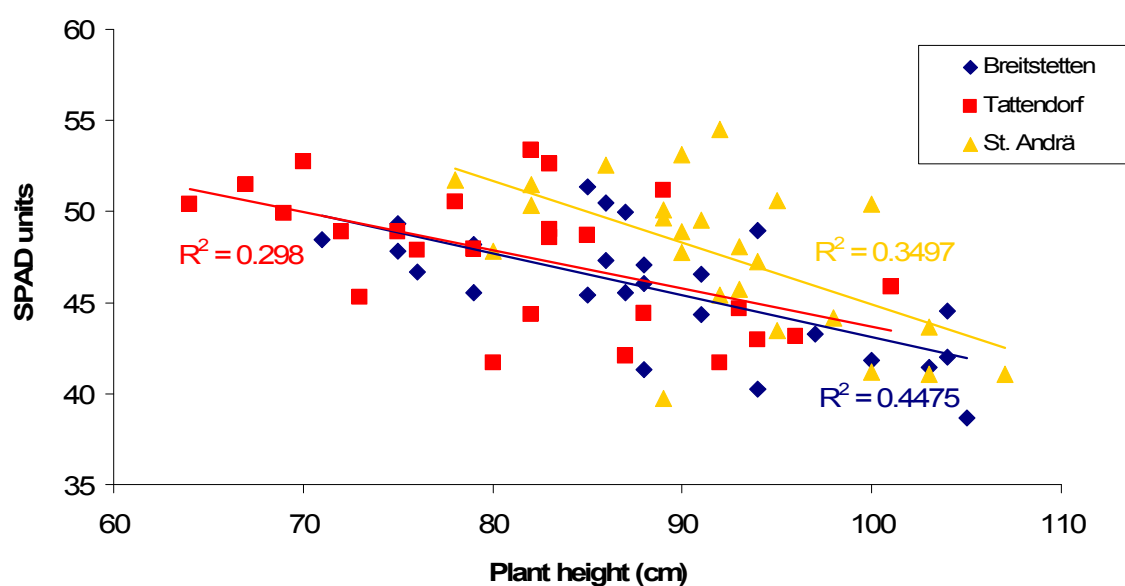


Figure 40: Intervarietal correlation between the plant height and the chlorophyll content of the core set

The stomatal conductance just showed a slight negative tendency in correlation to the plant height in the core set. The additional 72 genotypes supported this negative tendency with a negative correlation ($p \leq 0.01$) (Table 12).

3.3.4. Novel selection criteria correlated with the yield and the quality parameters

The electrical capacitance was negatively correlated ($p \leq 0.01$ and $p \leq 0.05$) with the test weight (Figure 41) and the thousand grain weight (Table 13).

Table 13: Correlation coefficients between the novel selection criteria and the ear density, the yield and the quality parameters (core set on the left and supplemental set on the right)

		BEST	KOEQ	HLGW	TKGN	RPRT			BEST	KOEQ	HLGW	TKGN	RPRT
EKA	Bre	.272	-.231	-.005	-.181	.168	EKA	Bre		-.017	-.014		
	Tat	.367	.095	-.631**	-.405*	-.140		Tat		.062	-.235*		
	St. A	-.128	.022	-.175	.440*	-.014		St. A					
OSP	Bre						OSP	Bre					
	Tat	.114	.250	-.300	-.213	-.332		Tat					
	St. A							St. A					
OTE	Bre	.147	.093	.040	.258	-.083	OTE	Bre		.110	.393**		
	Tat	.239	.219	-.354	-.359	-.257		Tat		.216	-.130		
	St. A							St. A					
SPD	Bre	.169	-.112	-.320	-.394	.018	SPD	Bre		.037	-.268*		
	Tat	-.037	.021	-.255	-.185	-.312		Tat		.311**	-.256*		
	St. A	.099	.479*	-.087	-.424*	-.648**		St. A		.413**	-.044		
STO	Bre	.126	-.130	.039	.132	.210	STO	Bre		-.013	-.192		
	Tat	.141	-.024	-.489*	-.298	-.107		Tat		.209	-.078		
	St. A							St. A					

* = significant at the level $p \leq 0.05$

** = significant at the level $p \leq 0.01$

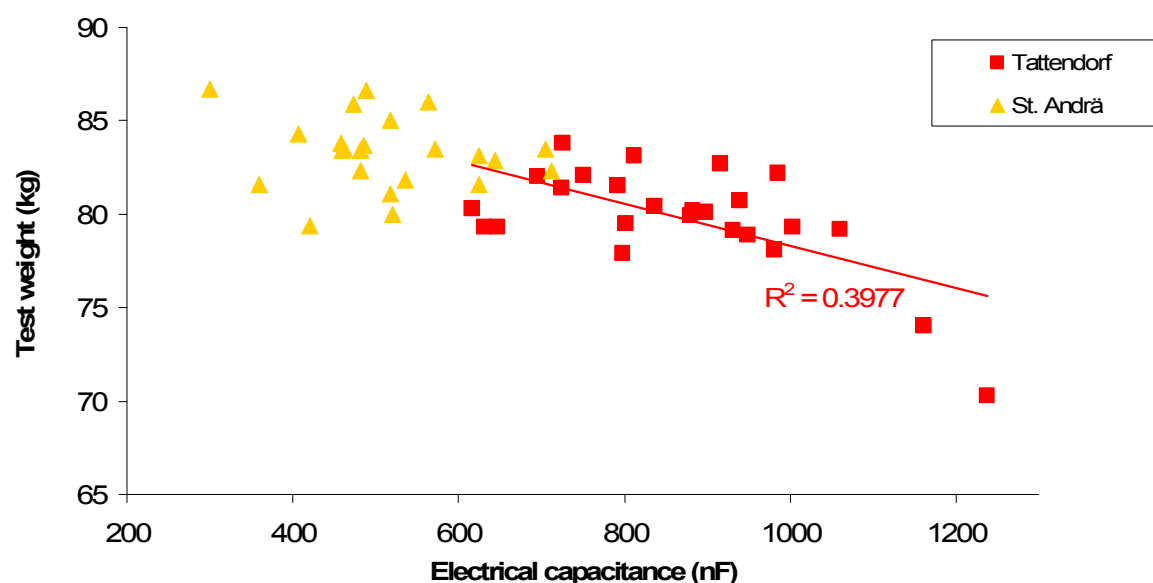


Figure 41: Intervarietal correlation between the electrical capacitance and the test weight of the core set

(capacitance values and their interactions in Breitstetten are not displayed because capacitance values of the wheat roots were very low)

No correlation was found between the osmotic potential and the yield or the quality parameters. The same result was noticed for the canopy temperature and the yield. Only in the supplemental set a positive correlation ($p \leq 0.01$) between the canopy temperature and the test weight was shown (Table 13).

As illustrated in Figure 42 the chlorophyll content was positively correlated to the grain yield in the core set ($p \leq 0.05$) as well as in the additional 72 genotypes ($p \leq 0.01$).

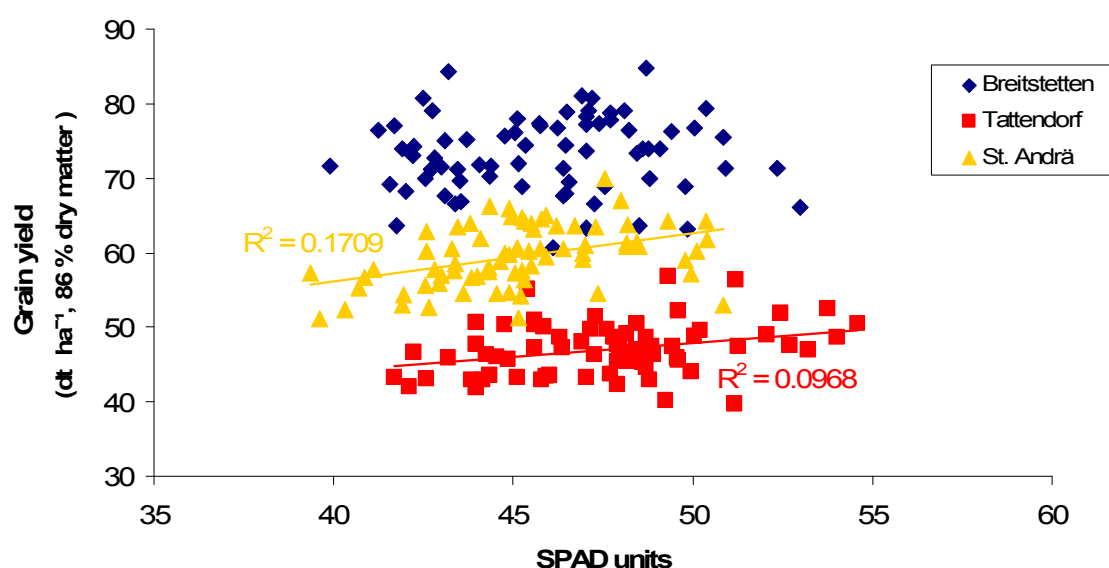


Figure 42: Intervarietal correlation between the chlorophyll content and the grain yield of the additional 72 genotypes

A negative tendency was found between the chlorophyll content and the quality parameters (test weight, thousand grain weight and protein content). A negative significance ($p \leq 0.05$) was shown for the test weight in the supplemental set (Table 13).

In the core set the correlation between the chlorophyll content and the thousand grain weight (Figure 43) as well as the protein content was negative ($p \leq 0.05$ and $p \leq 0.01$) (Table 13).

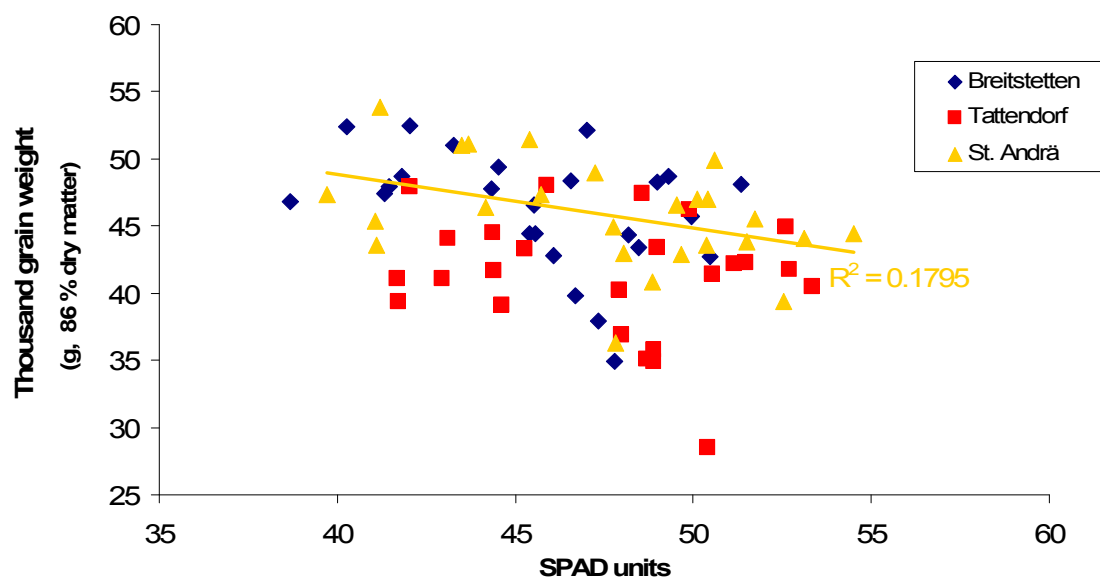


Figure 43: Intervarietal correlation between the chlorophyll content and the thousand grain weight of the core set

The stomatal conductance was negatively correlated ($p \leq 0.05$) with the test weight (Figure 44). This negative tendency was also shown in the supplemental set but without any significance.

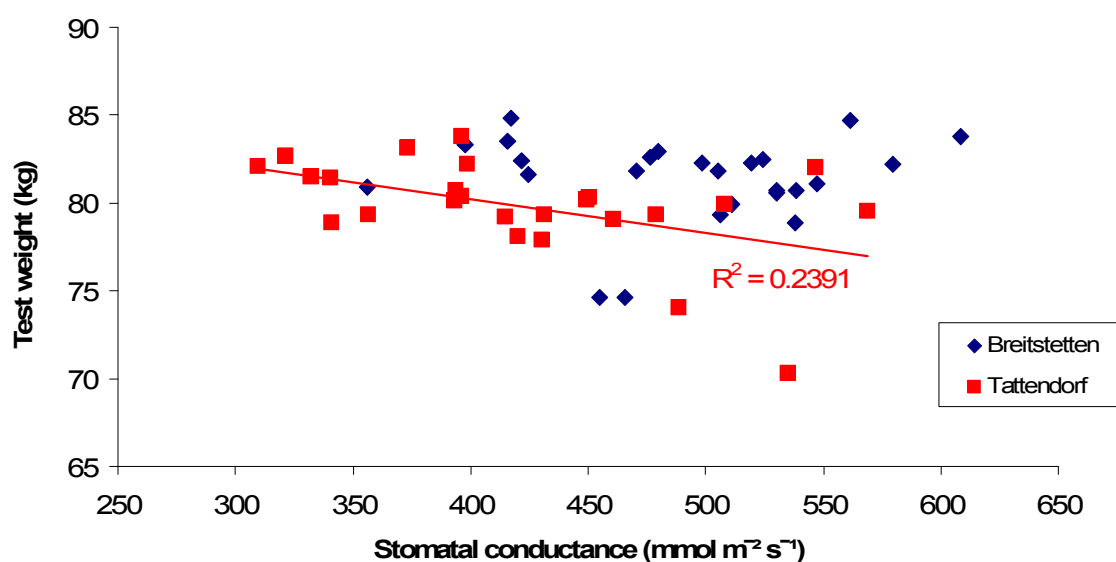


Figure 44: Intervarietal correlation between the stomatal conductance and the test weight of the core set
(no stomatal conductance measurements were performed in St. Andrä)

3.3.5. Correlations among the stress indicators

In the core set a negative interaction ($p \leq 0.01$) was noticed between the leaf rolling and the leaf senescence but only at the first scoring date (Table 14). For the other leaf senescence scorings no correlation was shown.

Large location based differences were detected in the supplemental set. In Tattendorf the leaf rolling was negatively correlated ($p \leq 0.05$) with the first scoring of leaf senescence. In Breitstetten a positive interaction ($p \leq 0.01$) was noticed. This positive significance stayed the same at the second and third scoring date.

Table 14: Correlation coefficients among the stress indicators (core set on the left and supplemental set on the right)

		BLRO	SZF1	SZF2	SZF3
BLRO	Bre		.123	.017	.265
	Tat	/	-.612**	-.121	-.311
	St. A				
SZF1	Bre			.780**	.582**
	Tat	/		.596**	.689**
	St. A				
SZF2	Bre				.761**
	Tat	/			.786**
	St. A				
SZF3	Bre				
	Tat	/			
	St. A				

		BLRO	SZF1	SZF2	SZF3
BLRO	Bre		.341**	.488**	.370**
	Tat	/	-.286*	-.156	-.035
	St. A				
SZF1	Bre			.875**	.722**
	Tat	/		.711**	.742**
	St. A				
SZF2	Bre				.889**
	Tat	/			.886**
	St. A				
SZF3	Bre				
	Tat	/			
	St. A				

* = significant at the level $p \leq 0.05$

** = significant at the level $p \leq 0.01$

Within the leaf senescence scoring dates positive correlations ($p \leq 0.01$) were detected, in the core set as well as in the supplemental set (Table 15).

3.3.6. Stress indicators correlated with the growth stages and the plant morphology

The leaf rolling showed positive interactions ($p \leq 0.01$) with the heading (Figure 45) and flowering date, in the core set as well as in the supplemental set ($p \leq 0.05$).

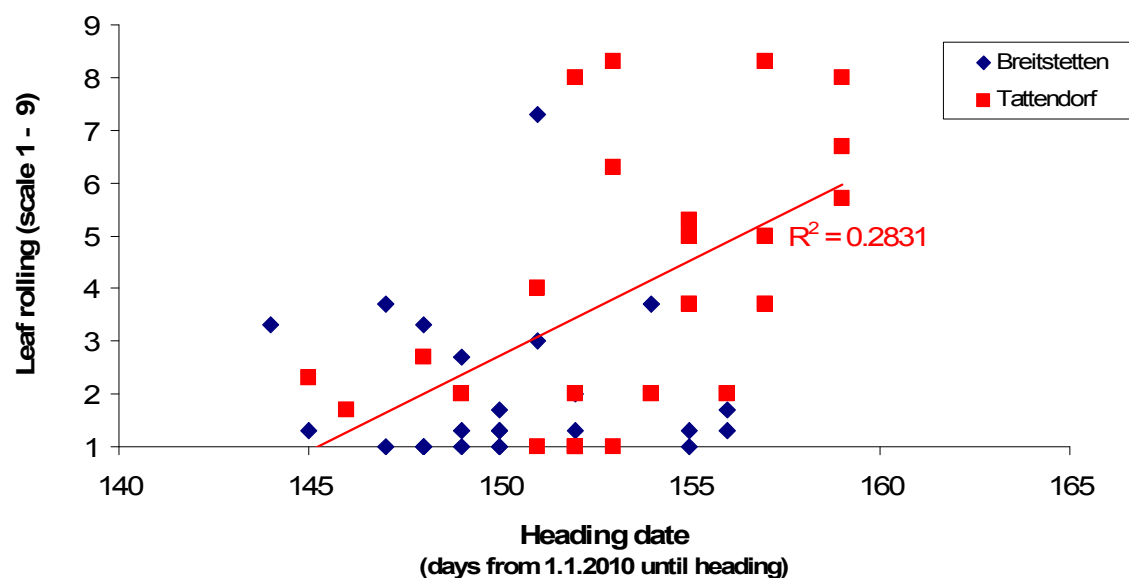


Figure 45: Intervarietal correlation between the heading date and the leaf rolling of the core set (no scoring of leaf senescence in St. Andrä)

No correlation was noticed for the physiological grain maturity date and the leaf rolling (Table 15). However, in the additional 72 genotypes a negative correlation ($p \leq 0.01$) was found between these two parameters.

No interaction between the leaf rolling and the plant height was indicated.

Table 15: Correlation coefficients between the stress indicators, the growth stages and the plant height (core set on the left and supplemental set on the right)

		DTAE	DTBL	DTGR	WHOE
BLRO	Bre	.103	.108	-.070	.079
	Tat	.541**	.563**	.291	.056
	St. A				
SZF1	Bre	-.517**	-.520**	-.615**	-.294
	Tat	-.530**	-.624**	-.539**	.063
	St. A				
SZF2	Bre	-.642**	-.530**	-.729**	.056
	Tat	-.604**	-.521**	-.729**	.256
	St. A				
SZF3	Bre	-.578**	-.442*	-.689**	.213
	Tat	-.502*	-.449*	-.683**	.340
	St. A				

		DTAE	DTBL	DTGR	WHOE
BLRO	Bre	-.160	-.167	-.357**	.011
	Tat	.270*	.285*	.058	-.073
	St. A				
SZF1	Bre	-.625**	-.622**	-.654**	.018
	Tat	-.820**	-.855**	-.579**	.060
	St. A				
SZF2	Bre	-.316**	-.331**	-.500**	.330**
	Tat	-.535**	-.531**	-.552**	.286*
	St. A				
SZF3	Bre	-.179	-.186	-.364**	.364**
	Tat	-.457**	-.461**	-.615**	.208
	St. A				

* = significant at the level $p \leq 0.05$

** = significant at the level $p \leq 0.01$

As illustrated in Figure 46 negative interactions ($p \leq 0.01$) were shown between the leaf senescence scoring dates and the physiological grain maturity stage as well as for the other growth stages. The same reaction was detected in the supplemental set (Table 15).

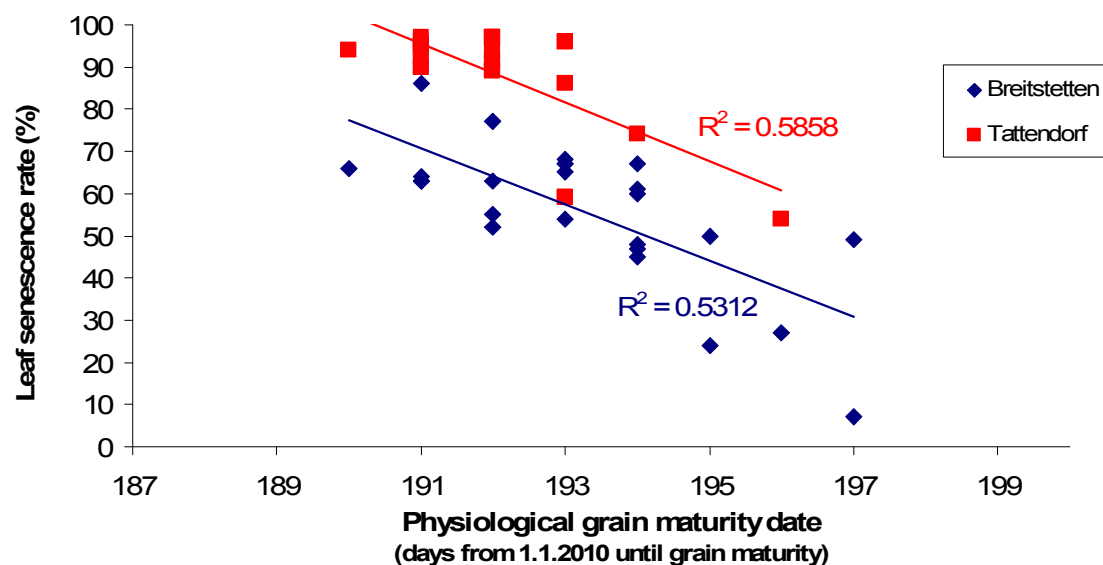


Figure 46: Intervarietal correlation between the physiological grain maturity date and the leaf senescence rate (second scoring date) of the core set
(no rating of leaf senescence in St. Andrä)

In the core set a positive tendency was noticed for the correlation of the leaf senescence and the plant height (Table 15). This tendency was supported by a positive correlation ($p \leq 0.01$) in the supplemental set (Figure 47).

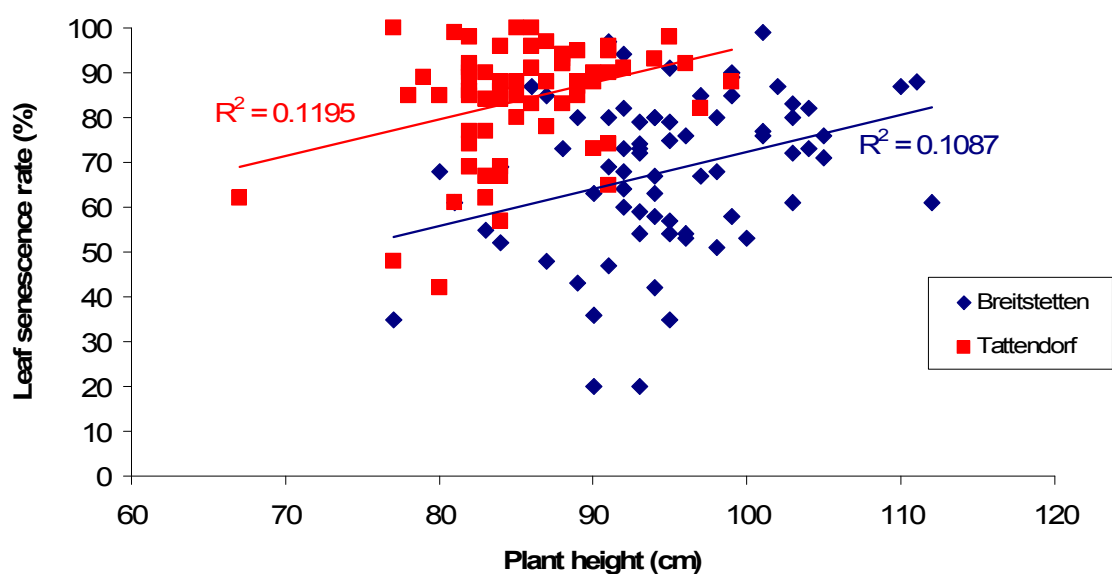


Figure 47: Intervarietal correlation between the plant height and the leaf senescence rate (second scoring date) of the supplemental set
(no rating of leaf senescence in St. Andrä)

3.3.7. Stress indicators correlated with the yield and the quality parameters

The core set as well as the supplemental set showed the same correlations between the stress indicators, the ear density, the yield and the quality parameters (Table 16).

Table 16: Correlation coefficients between the stress indicators, the ear density, the yield and the quality parameters (core set on the left and supplemental set on the right)

		BEST	KOEQ	HLGW	TKGN	RPRT			BEST	KOEQ	HLGW	TKGN	RPRT
BLRO	Bre	-.363	.072	.059	.023	-.155	BLRO	Bre		-.172	.270*		
	Tat	.438*	.317	-.467*	-.251	-.408*		Tat		.093	-.233*		
	St. A							St. A					
SZF1	Bre	.225	-.622**	.134	-.341	.596**	SZF1	Bre		-.689**	.146		
	Tat	-.298	-.040	.419*	.395	.119		Tat		-.020	.382**		
	St. A							St. A					
SZF2	Bre	-.080	-.788**	.567**	.107	.792**	SZF2	Bre		-.576**	.307**		
	Tat	-.432*	-.153	.653**	.665**	.175		Tat		-.096	.545**		
	St. A							St. A					
SZF3	Bre	-.272	-.740**	.666**	.269	.735**	SZF3	Bre		-.532**	.364**		
	Tat	-.446*	-.124	.625**	.636**	.193		Tat		.044	.358**		
	St. A							St. A					

* = significant at the level $p \leq 0.05$

** = significant at the level $p \leq 0.01$

The leaf rolling was positively correlated with the ear density (Table 16).

A negative interaction ($p \leq 0.05$) was noticed between the leaf rolling and the test weight as well as for the grain protein content (Figure 48).

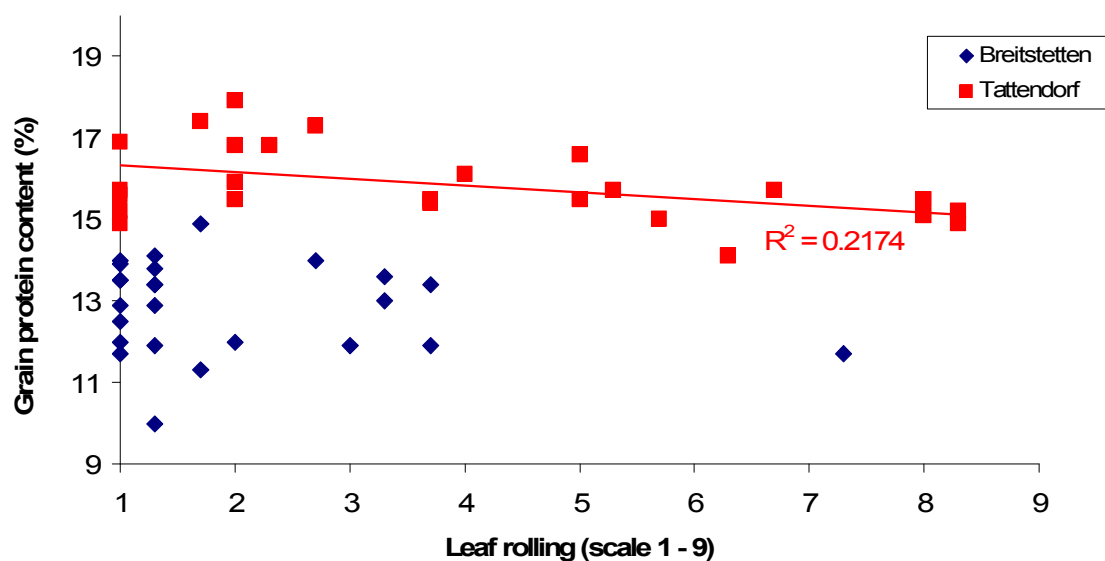


Figure 48: Intervarietal correlation between the leaf rolling and the grain protein content of the core set
(no rating of leaf rolling in St. Andrä)

The leaf senescence was positively correlated ($p \leq 0.05$) with the ear density.

In the core set as well as in the supplemental set a negative correlation ($p \leq 0.01$) was shown between the grain yield and the leaf senescence at all three scoring dates (Table 16 and Figure 49).

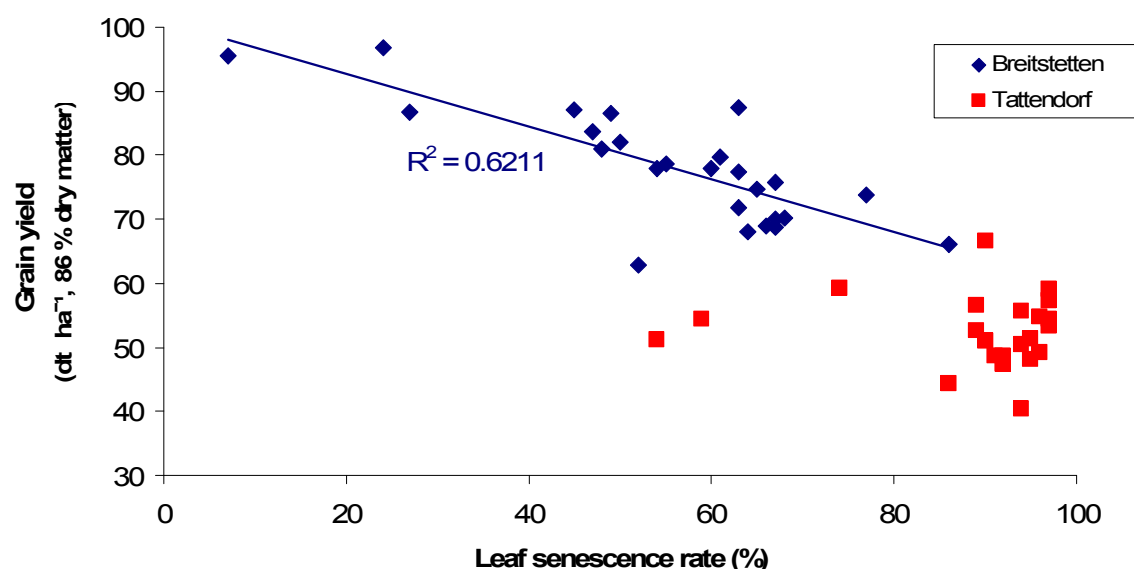


Figure 49: Intervarietal correlation between the leaf senescence rate (second scoring date) and the grain yield of the core set
(no rating of leaf senescence in St. Andrä)

The quality parameters (test weight, thousand grain weight and grain protein content) were positively correlated ($p \leq 0.05$ and $p \leq 0.01$) with the leaf senescence dates (Figure 50).

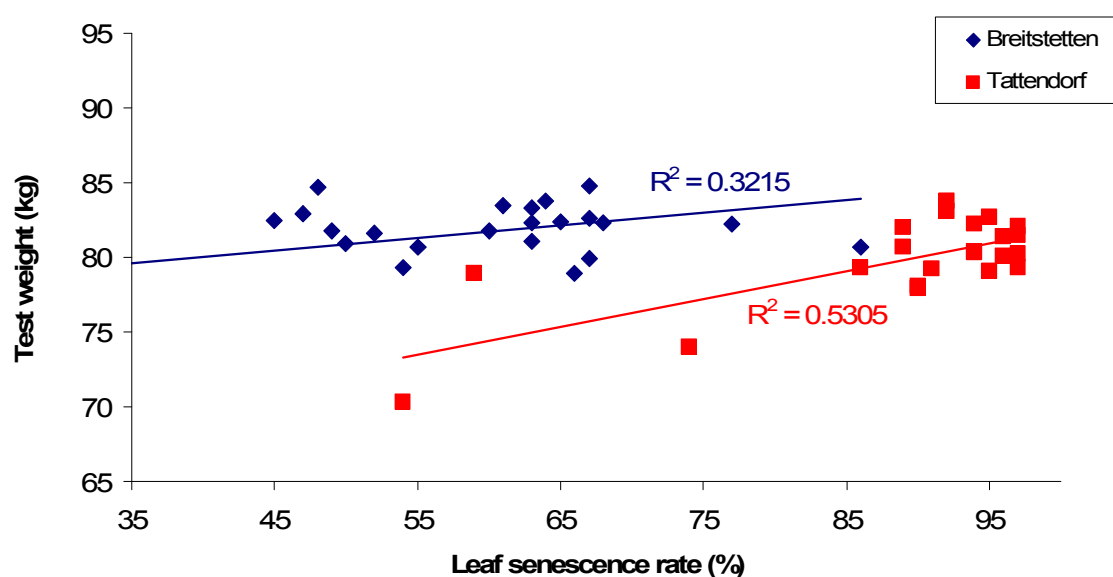


Figure 50: Intervarietal correlation between the leaf senescence rate (second scoring date) and the test weight of the core set
(no rating of leaf senescence in St. Andrä)

3.3.8. The Yield and the quality parameters correlated with the growth stages and the plant morphology

The ear density showed positive interactions ($p \leq 0.05$) with the heading and physiological grain maturity date (Table 17).

Table 17: Correlation coefficients of the ear density, the yield and the quality parameters correlated with the growth stages and the plant morphology (core set on the left and supplemental set on the right)

		DTAE	DTBL	DTGR	WHOE
BEST	Bre	-.202	-.290	-.117	-.528**
	Tat	.397*	.353	.398*	-.191
	St. A	.228	.245	.234	-.453*
KOEQ	Bre	.657**	.642**	.730**	.253
	Tat	.360	.216	.127	.187
	St. A	.182	.147	.180	-.377
HLGW	Bre	-.345	-.178	-.329	.528**
	Tat	-.417*	-.336	-.688**	.469*
	St. A	-.360	-.380	-.450*	.457*
TKGN	Bre	.157	.259	.085	.602**
	Tat	-.274	-.221	-.513**	.389
	St. A	.203	.184	.116	.508**
RPRT	Bre	-.671**	-.634**	-.725**	-.109
	Tat	-.430*	-.262	-.205	-.131
	St. A	.116	.153	.002	.473*

		DTAE	DTBL	DTGR	WHOE
BEST	Bre				
	Tat				
	St. A				
KOEQ	Bre	.469**	.424**	.351**	.014
	Tat	-.121	-.140	-.176	-.202
	St. A	.133	.071	.349**	-.466**
HLGW	Bre	-.319**	-.247*	-.278*	.334**
	Tat	-.519**	-.516**	-.197	.424**
	St. A	-.044	-.033	.005	.117
TKGN	Bre				
	Tat				
	St. A				
RPRT	Tat				
	St. A				

* = significant at the level $p \leq 0.05$

** = significant at the level $p \leq 0.01$

Another correlation, namely a negative one ($p \leq 0.05$ and $p \leq 0.01$) was found between the ear density and the plant height (Figure 51).

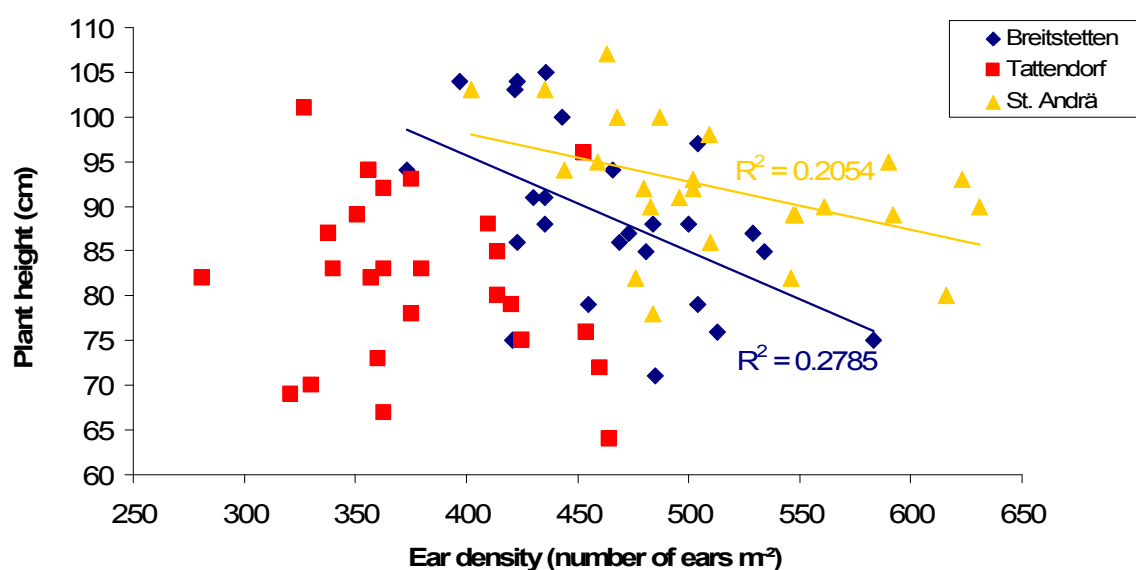


Figure 51: Intervarietal correlation between the ear density and the plant height of the core set

Not only in the core set but also in the supplemental set the grain yield was positively correlated ($p \leq 0.01$) with the growth stages (heading, flowering and physiological grain maturity date) (Figure 52).

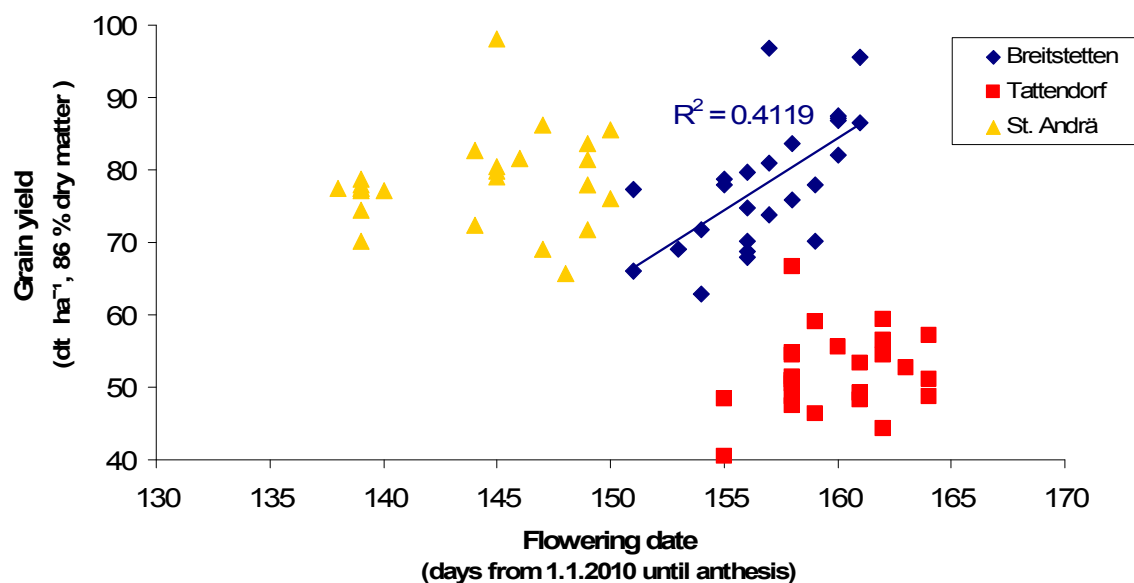


Figure 52: Intervarietal correlation between the flowering date and the grain yield of the core set

In the supplemental set the grain yield continued to be negatively correlated ($p \leq 0.01$) with the plant height (Table 17).

A negative interaction ($p \leq 0.05$ and $p \leq 0.01$) was found between the test weight and all the growth stages (Figure 53), in the core set as well as in the supplemental set.

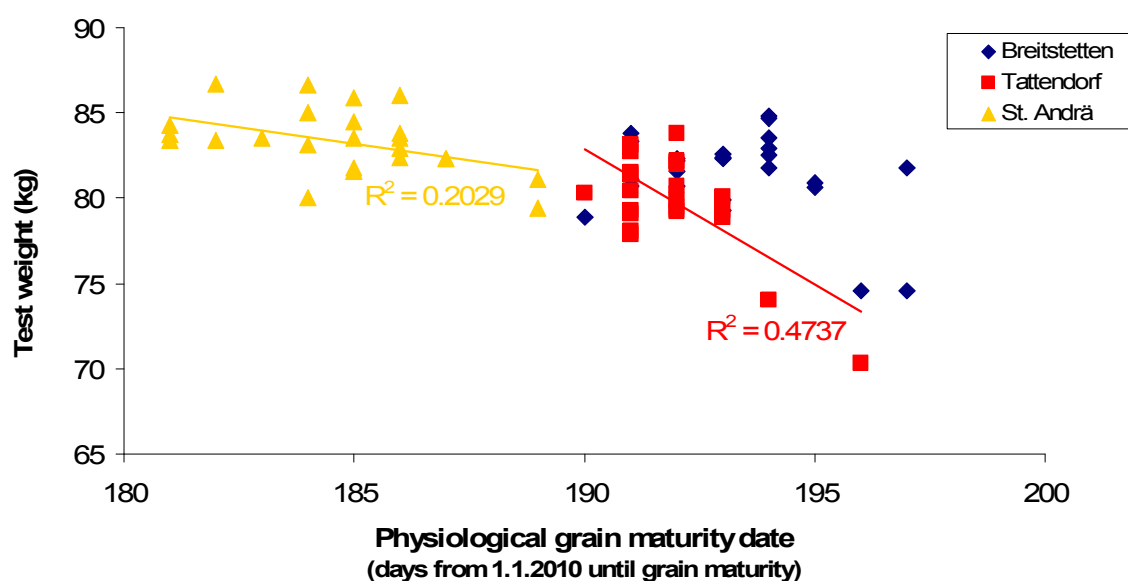


Figure 53: Intervarietal correlation between the physiological grain maturity date and the test weight of the core set

A positive correlation ($p \leq 0.01$) was noticed between the test weight and the plant height (Table 17 and Figure 54) too.

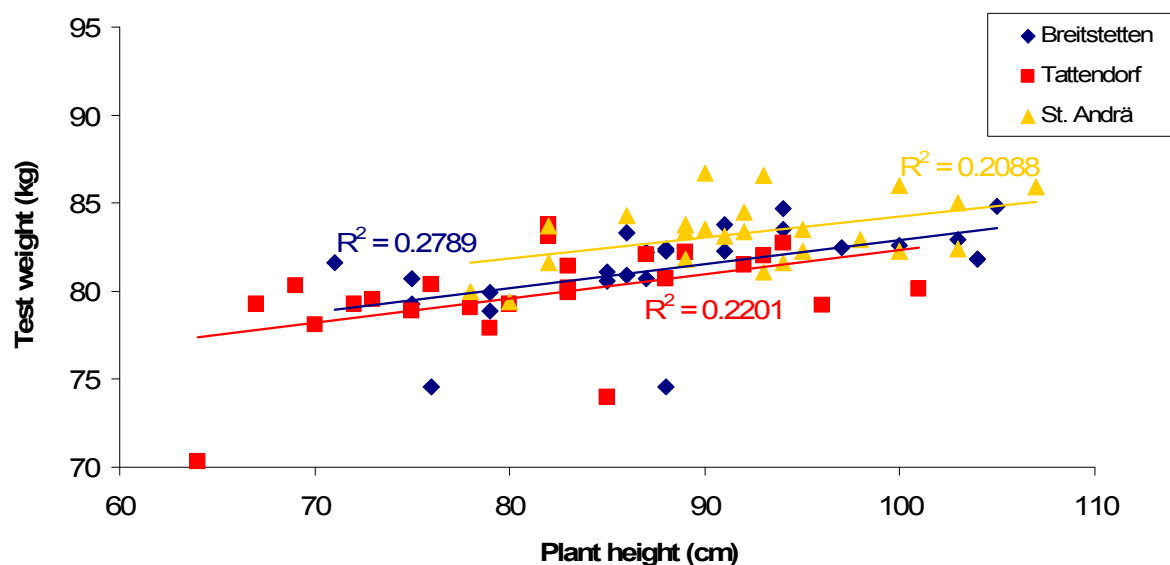


Figure 54: Intervarietal correlation between the plant height and the test weight of the core set

As shown in Table 17 the thousand grain weight was negatively correlated ($p \leq 0.01$) with the physiological grain maturity date. A positive interaction ($p \leq 0.01$) was found between the thousand grain weight and the plant height.

For the grain protein content and the growth stages a negative correlation ($p \leq 0.05$ and $p \leq 0.01$) was noticed (comparable to the other quality parameters). The interaction was positive between the grain protein content and the plant height (Table 17) too.

4. DISCUSSION

The present study gave a brief survey of indirect selection criteria for drought stress tolerance in wheat with emphasis on the novel selection criteria. Due to the unsuitable weather conditions this year (2010) it was not possible to compare drought stressed cultivars with non stressed controls. All observations were performed in the absence of drought and therefore the results in hand did not seem to help verifying effective selection criteria for drought tolerant varieties. This assumption was negated by several researchers (Chander and Singh 2008, Rajaram et al. 1996, Richards 1996, Uddin et al. 1992). They reported that selection for drought tolerant cultivars is more efficient under non stressed conditions. In favourable environments varieties with a high yield potential can be selected and they seem to maintain high yield under stressed environments.

The results indicate the need of more research regarding the selection criteria for drought tolerant varieties. Furthermore, the validity of these results is limited because the data arise from one year of cultivation.

The hypothesis was devised as follows:

H_0 = Novel selection criteria can be used for detecting drought tolerant winter wheat genotypes.

Based on the present results, this hypothesis can neither be corroborated nor be rejected. The statement can just be strengthened due to the fact that no drought conditions were predominated and that the data arise from a one year study.

Nevertheless, for the detection of drought tolerant varieties there is the need of an appropriate combination of different selection criteria. Because of this established fact, the presented correlations will be further discussed.

4.1. Correlations among the novel selection criteria

In the core set no significant correlations were noticed among the novel selection criteria. The findings were in disagreement with the statement by Izanloo et al. (2008), Reynolds et al. (2001) and Blum (1989). These researchers reported a significant negative correlation between stomatal conductance and canopy temperature but only under drought conditions. If stomatal conductance is reduced, evaporative cooling will be less and hence plant temperature will rise. Contrasting data were also shown in the supplemental set where a positive interaction ($p \leq 0.05$) between stomatal conductance and canopy temperature was detected. Due to the fact that this year was characterised by a precipitation surplus the non significant correlation in the core set is in agreement with Izanloo et al. (2008).

Although there were no significances noticed some tendencies among the novel selection criteria could be found. In the supplemental set these tendencies were partly enhanced with significances. Here, the electrical capacitance of roots was positively related with the canopy temperature and the stomatal conductance. Similarly results were obtained by Reynolds et al. (1998) and Davies and Zhang (1991) who reported a positive correlation between stomatal conductance and root size. High stomatal conductance indicates that the root system takes up more water from the soil and therefore the electrical capacitance is higher.

Another tendency of the core set was supported in the supplemental set: the association between chlorophyll content and stomatal conductance. These results are in conformation with Borrell et al. (2000) who stated that varieties with higher chlorophyll content stay green for longer, maintain more photosynthetically active leaves and show higher stomatal conductance (transpiration efficiency) under post-anthesis drought conditions.

4.2. Novel selection criteria correlated with the stress indicators

A negative relationship ($p \leq 0.05$ and $p \leq 0.01$) was shown between the electrical capacitance of roots and the leaf senescence dates. Higher capacitance values of wheat roots resulted in lower leaf senescence. These results are in accordance with Reynolds et al. (2001). They concluded that low leaf senescence indicates well water supplied soil conditions and eventually deeper roots. Through the assimilation from the photosynthetic active leaves, soil water is extracted and the capacitance value of the roots is high. Nevertheless, leaf senescence is a type of cell death program and therefore also a phenomenon that emerges naturally at later growth stages (Araus et al. 2008, Tahiro 2002). For screening the senescence rate at later growth stages it is difficult to distinguish between drought-induced leaf senescence (Munné-Bosch and Alegre 2004) and natural-induced one.

In the core set a positive association ($p \leq 0.01$) was detected between osmotic potential and leaf rolling. The lower and more negative the osmotic potential was, the fewer was the leaf rolling. The explanation can be made on the basis of osmotic adjustment. Several researchers (Kramer and Boyer 1995, Ludlow and Muchow 1990, Blum 1988, Morgan 1984) reported that osmotic adjustment is an effective component of drought tolerance. As soon as the water potential of the cell is decreased osmotic adjustment causes an accumulation of solutes. Through this accumulation the osmotic potential is lowered and water is attracted into the cell. The consequence is the maintainance of the turgor pressure (Babu et al. 1999). Due to the fact that leaf rolling is often the result of turgor loss, the low leaf rolling at a more negative osmotic potential can be explained. This conclusion is in conformity with those of Steponkus et al. (1982), Turner and Jones (1980), Cutler et al. (1980a, 1980b) and Hsiao et al. (1976).

Nevertheless, leaf rolling as a visual indicator for selecting drought tolerant crops (IRRI 1982, O'Toole and Cruz 1979, Loresto et al. 1976) must be used with caution due to the fact that leaf rolling also depends on the cultivar (Jones 1979). The same statement was confirmed by Hsiao et al. (1984) who reported that the degree of leaf rolling depends on the ability to adjust osmotically and therefore on the genotype. According to Loresto et al. (1976) a small degree of leaf rolling indicates that the process of dehydration avoidance is performed through the development of deep roots.

A negative relationship ($p \leq 0.05$) was reported between canopy temperature and leaf rolling. The higher the canopy temperature the lower was the degree of leaf rolling. These results are supported by the findings of earlier researchers like Tardieu (2005), Loss and Siddique (1994) and De Datta et al. (1988). They concluded that leaf rolling is a reduction of the effective leaf area as well as a decrease in leaf transpiration and this results in higher canopy temperatures.

Only in the supplemental set the chlorophyll content showed negative interactions ($p \leq 0.05$) with the leaf senescence. The interrelation that a low chlorophyll content results in a higher leaf senescence rate is obvious. Similar results were reached by Izanloo et al. (2008) and Borrell et al. (2000) who also observed that cultivars with high chlorophyll content stayed green for a longer period. Munné-Bosch and Alegre (2004), Lu et al. (2002) and Lu and Zhang (1998) noticed that during drought stress this connection could be a type of programmed cell death in order to survive under drought conditions.

In the core set a negative correlation ($p \leq 0.05$) was noticed between stomatal conductance and leaf senescence, a fact which is supported by Borrell et al. (2000) too. Low leaf senescence contributes to an improved transpiration efficiency and therefore a high stomatal conductance.

4.3. Novel selection criteria correlated with the growth stages and the plant morphology

The electrical capacitance of roots showed positive correlations ($p \leq 0.01$) with all three growth stages. Early maturing varieties had low capacitance values. The capacitance measurements were performed around anthesis. At this growth stage the maximum size of root system is reached (Barraclough and Leigh 1984, Boehm 1978) and the active root mass starts to decrease at the following growth stages (Schroetter et al. 2006). Due to the fact that early maturing genotypes have shorter growth periods (Sleper and Poehlman 2006) it can be assumed that the active root mass of these genotypes has already been lignified. Therefore the electrical capacitance attained lower values. No comparable correlations and results were found in literature.

A negative association ($p \leq 0.01$) was detected between the chlorophyll content and the growth stages. Early maturing genotypes showed a higher chlorophyll content than late maturing genotypes. No comparable correlations were found in literature. However, a possible explanation could be that late maturing genotypes have to face heat and drought stress. Due to this fact they can reduce the risk of desiccation through a lower chlorophyll content. According to Reynolds et al. (2005) and Blum (1988) pale green leaves can decrease the radiation absorbance and protect the plant from dehydration.

Another negative relationship ($p \leq 0.01$) was found between the chlorophyll content and the plant height. Short cultivars show a lower biomass per plant than tall varieties. Because of this fact the chlorophyll content of tall cultivars might be diluted as a result of distribution on higher biomass. Similar results have been detected earlier by Kaushik and Sharma (1985) and Harada and Nakayama (1971).

In the core set the stomatal conductance showed a negative tendency with plant height. This tendency was supported in the supplemental set with a negative correlation ($p \leq 0.01$). These results are in conformation with the reports of Bahar et al. (2009) and Fischer et al. (1981).

4.4. Novel selection criteria correlated with the yield and the quality parameters

Although there exist several findings of a positive relationship between root growth and grain yield (Chloupek et al. 2010, Lambers et al. 2008, Jordan et al. 1983a) no significance was detected in this present study. Nevertheless, the electrical capacitance showed a negative correlation ($p \leq 0.05$ and $p \leq 0.01$) with the test weight and the thousand grain weight. Varieties with a bigger root system and therefore a higher capacitance value result in poor test and thousand grain weight. One possible interpretation of these results is a competition for assimilates between the roots and the grain fill. Varieties that put emphasis on a big and deep root system in order to take up more water from the soil, translocate assimilates to the below-ground biomass. This assimilate shifting results in lower test and thousand grain weight. A very similar conclusion was reached by Pugnaire et al. (1994) and Brouwer (1962) who stated that under drought stress a partitioning of assimilates to the root would be favoured.

The canopy temperature showed a significant positive correlation ($p \leq 0.01$) to the test weight but just in the supplemental set. These findings are in disagreement with the reports of Pinto et al. (2008) who stated that genotypes with cooler canopies had the ability to fill their grains better. A possible explanation for the positive correlation could be given through the fact that the canopy temperature measurement is influenced by many factors (Reynolds et al. 2001). Non reproducible and critical values are the result.

A positive relationship ($p \leq 0.01$) was noticed between the chlorophyll content and the grain yield, but just in the supplemental set. The higher the chlorophyll content, the higher was the grain yield. These results are in accordance with Gutierrez-Rodriguez et al. (2004) and Borrell et al. (2000). Tahiro (2002) and Reynolds et al. (1992) confirmed this correlation as well but only under heat stress conditions.

The association between the chlorophyll content and the quality parameters (test weight, thousand grain weight and protein content) was negative ($p \leq 0.05$ and $p \leq 0.01$). These findings are in disagreement with the statement by Izanloo et al. (2008) and Spano et al. (2003) who reported a positive correlation between chlorophyll content and grain size. These contradictory results could occur through different measuring dates as well as through different environmental conditions (drought or irrigated conditions).

In the core set there was a negative interaction ($p \leq 0.05$) detected between stomatal conductance and test weight. Varieties with a high stomatal conductance (and therefore a low canopy temperature) result in lower test weights. As already mentioned for the correlations between canopy temperature and test weight these results were in contrast to the findings of Pinto et al. (2008). They reported that genotypes with a low canopy temperature (a high conductance) can fill their grains more successfully which would lead to a positive association between stomatal conductance and grain yield (Bunce 1981, Shimshi and Ephrat 1975). As already mentioned above could this contradiction result from a different measuring date or a different environmental condition.

4.5. Correlations among the stress indicators

A positive and negative correlation ($p \leq 0.05$ and $p \leq 0.01$) was detected between leaf rolling and leaf senescence. These converse results are due to location based differences. Wheat plants in Tattendorf were grown on stony and light soil resulting in poorer conditions for the varieties compared with those in Breitstetten. Furthermore genotypes in Tattendorf were exposed to a short, moderate late-season drought. As a response to water deficit, wheat plants in Tattendorf reduced their leaf size through leaf rolling (Tardieu 2005). The negative interrelation is shown with a low senescence rate in order to maintain photosynthetic activity.

One possible interpretation of the positive correlations in Breitstetten is the phenomenon that leaf senescence as well as leaf rolling can occur as a consequence of the natural aging process (Araus et al. 2008, Tahiro 2002, Smith et al. 1995).

The interrelation of the leaf senescence dates is self-explanatory because a high leaf senescence rate at the first scoring date will result in a higher rate at the following screening dates.

4.6. Stress indicators correlated with the growth stages and the plant morphology

Leaf rolling is positively associated ($p \leq 0.05$ and $p \leq 0.01$) with the heading, flowering and maturity date. Late maturing genotypes show a greater leaf rolling. Similar results were reported by Blum and Pnuel 1990, Hadjichristodoulou 1989, Marshall 1987, Fischer 1981 and Derera et al. 1969 who stated that late maturing cultivars are exposed not only to late-season drought but also to heat stress and react with leaf rolling. Early maturing varieties with a shorter growth period (Sleper and Poehlman 2006) are therefore better adapted to late-season water scarcity.

A negative correlation ($p \leq 0.01$) was found between leaf senescence and heading as well as flowering and maturity date. Due to the fact that early maturing genotypes have a shorter growth period, leaf senescence occurs first at these cultivars. Here, the process of natural aging has to be considered (Araus et al. 2008, Tahiro 2002, Smith et al. 1995).

In the supplemental set a positive association ($p \leq 0.01$) was detected between the leaf senescence and the plant height. In literature no similar correlation was found. A possible explanation could be that taller plants absorb more radiation resulting in a higher sensitivity towards drought and heat. Their response is a reduction in leaf size through leaf senescence. Another possible interpretation is that taller varieties show a lower chlorophyll content (Table 12) and therefore they will senescent earlier.

4.7. Stress indicators correlated with the yield and the quality parameters

Leaf rolling was positively correlated ($p \leq 0.05$) with the ear density. A high ear density results in a high leaf rolling rate. In literature no similar correlations were detected. A possible interpretation could be that the temperature within the plot increases due to a high number of ears. Leaves react sensitively to this temperature rise and reduce their leaf size through leaf rolling. More dense stands are also prone to higher transpiration and thus earlier drought effects.

A negative relationship ($p \leq 0.05$) was detected between leaf rolling and two quality parameters (test weight and protein content). As mentioned earlier, leaf rolling is an effective way to decrease leaf size (Tardieu 2005, Hsiao et al. 1984). By reducing the photosynthetic active leaf area less radiation can be absorbed which will lead to less assimilate production (Loss and Siddique 1994). A lower test weight and protein content might be the consequences.

The leaf senescence rates were in negative association ($p \leq 0.05$ and $p \leq 0.01$) with the ear density and the grain yield. These results are substantiated with those of Kandić et al. (2009) and Borrell et al. (2000). A low senescence rate maintains a higher transpiration efficiency resulting in prolonged assimilation.

Leaf senescence was found in positive correlation ($p \leq 0.01$) with all quality parameters. These findings are in disagreement with the statement by Spano et al. (2003), Richards et al. (2001) and Gelang et al. (2000). According to these authors only an extended duration of grain filling (low senescence rate) will result in high quality and larger grains. The positive correlation within this study could be approved through the detected negative correlation between the quality parameters and the growth stages (compare 4.8.). Early maturing genotypes reached a higher quality and due to the fact that these varieties showed a higher leaf senescence rate, this reported positive correlation could be explained.

4.8. Yield and quality parameters correlated with the growth stages and the plant morphology

The ear density was positively correlated ($p \leq 0.05$) with the heading and maturing date. Late maturing genotypes show a higher number in ears m^{-2} . These results are in accordance with Subhani and Chowdhry (2000) but in contrast with Khan et al. (2010) who reported a significant negative relationship between ears m^{-2} and days to maturity. Due to the fact that these two traits are considered as variety characteristics, Khan et al. (2010) could have used different genotypes within their study.

A negative association ($p \leq 0.05$) was noticed between ear density and plant height. Similar results have also been obtained by Khan et al. (2010), Kashif and Khaliq (2004), Subhani and Chowdhry (2000) and Krotova (1988). The assumption that tall cultivars show a low ear density can also be found in the Austrian Descriptive List of Varieties (AGES 2010).

The grain yield was positively correlated ($p \leq 0.01$) with the heading, flowering and maturing date. This result was supported by several researchers (Khan et al. 2010, Anwar et al. 2009, Asif et al. 2004, Van Ginkel et al. 1998, Uddin et al. 1992). Higher yields can be achieved by a longer growing season (Blum, 1993). Nevertheless negative interactions were detected by Singh et al. (1995) and Subhani and Chowdhry (2000) regarding the grain yield and days to heading and maturity. Another significant negative correlation was found between grain yield and days to flowering (Kandić et al. 2009) under irrigation and drought stress.

In the supplemental set the grain yield was negatively correlated ($p \leq 0.01$) with the plant height. Similar results have also been reported by Khan et al. (2010), Akram et al. (2008), Khaliq et al. (2004), Okuyama et al. (2004), Patil and Jain (2002), Shahid et al. (2002), Akbar et al. (1995), Chaudry et al. (1994), Li (1989) and Ahmad et al. (1980). According to Khan et al. (2010) taller plants yield lower due to lodging in these varieties, but no lodging occurred in the present trial. Additional tall genotypes accumulate a high percentage of dry matter in vegetative parts and therefore the grain yield could be affected by a lower harvest index.

Negative correlations ($p \leq 0.05$ and $p \leq 0.01$) were detected between the quality parameters (test weight, thousand grain weight and protein content) and the growth stages (date of heading, anthesis and maturity). Early maturing genotypes showed a higher test weight, thousand grain weight and protein content. These results are in accordance with Subhani and Chowdry (2000) and Van Ginkel et al. (1998). According to these researchers low grain yields are associated with high test weight and thousand grain weight. This assumption can be verified with the above mentioned positive correlation of grain yield and growth stages. Due to the fact that the protein content is negatively correlated with the grain yield (Blanco et al. 2006, Pleijel et al. 1999, Campbell et al. 1981) early maturing varieties result in high protein content. Another explanation could be found in the earlier reported positive correlation between the leaf senescence and the quality parameters (compare 4.7.). Within this present study early maturing genotypes showed a higher leaf senescence rate and resulted in higher test weight, thousand grain weight and protein content.

The quality parameters were positively associated ($p \leq 0.05$ and $p \leq 0.01$) with the plant height. Taller varieties showed high test weight, high thousand grain weight and high protein content. The present findings are similar to those of Khan et al. (2010), Akram et al. (2008), Belay et al. (1993), Eunus et al. (1986) and Sandhu and Mangat (1985) who also observed a positive relationship between plant height and thousand grain weight. A possible interpretation is that tall cultivars (mostly high quality wheat) obtain a loose grain arrangement on the ears. Therefore these grains reach big grain sizes in order to carry a high yield. The result is a high test weight, a high thousand grain weight and a high protein content (Oberforster 2010). As illustrated in Figure 55 GK Petur (on the left) shows a tight grain arrangement and is a short cultivar (on average 75 cm). Eurofit (on the right) reveals a loose grain arrangement and is ranked among the tall varieties (on average 97 cm).



Figure 55: Loose grain arrangement (GK Petur on the left) and tight grain arrangement (Eurofit on the right)

5. CONCLUSION

The present results as well as the literature indicate that the selection for drought tolerant varieties is very complex. Absolutely essential are effective selection criteria that can be used, on the one hand for screening a great quantity of genotypes and on the other hand for detecting drought tolerant varieties under field conditions. Due to this need, the novel selection criteria were tested and subsequently evaluated.

The electrical capacitance of roots (EKA) indicated the most correlations with the other parameters. This result underlines the importance of the roots. The measured root capacitance values provide an indication of root mass, size and length (Chloupek et al. 1999, Chloupek 1972). Drought tolerant varieties show high capacitance values, an increased root length and therefore a deep penetration in wet soil layers (Meyers et al. 1984, Mambani and Lal 1983, Hurd 1968). The reviewed cultivars did not show a significant genotype variation (Table 6). This criterion is easy to measure (with a LCR meter) and it reveals the status of the plant's root and its vitality. Nevertheless, the electrical capacitance of roots showed a non significant genotype effect and high variations within the replications of one plot. Therefore it has to be seen as a critical selection criterion and further studies are required for selecting drought tolerant genotypes.

The osmotic potential (OSP) is a component of osmotic adjustment, a mechanism that enables the plant to survive under drought conditions (Blum 1988, McGowan et al. 1984). Drought tolerant varieties show a high osmotic adjustment and therefore a low, more negative osmotic potential (Morgan 1983). Slight but significant differences among the varieties were obtained (Table 6). The osmotic potential seems to be an effective selection criterion but further research is required. More efficient information will be expected when drought stressed varieties are compared with well watered controls. Within this present study the osmotic potential was just associated with few other traits and therefore it has to be considered as a non effective criterion.

The canopy temperature (OTE) is a function of stomatal conductance (Blum 1989). Under early drought conditions, varieties with a low canopy temperature (and therefore a high transpiration rate and a high stomatal conductance) should be selected (Pinto et al. 2008, Munjal and Rena 2003, Hatfield et al. 1987). Within this study significant genotype variability was shown (Table 6). Although this method is easy to operate (with an infrared thermometer) this criterion has to be considered as a hardly reproducible one. There are many environmental factors (cloudiness, wind, air temperature, plant metabolism, radiation, humidity) that influence the readings of the infrared thermometer (Reynolds et al. 2001).

The detection of the chlorophyll content (SPD) seems to be an effective selection criterion for drought tolerant varieties. Significant genotype variability (Table 6) was indicated within the SPAD values. By means of these differences, more precisely by means of higher and lower chlorophyll contents, cultivars can be eventually divided into drought tolerant and drought sensitive ones (Izanloo et al. 2008, Reynolds et al. 1992). Because of the fact that this criterion is easy to measure (with the chlorophyll meter) and its low number of environmental influencing factors, it shows great promise for selecting drought tolerant genotypes.

The reduction of stomatal conductance (STO) is described by Chaves et al. (2003), Ray and Sinclair (1997), Ludlow and Muchow (1990) as a strategy to avoid dehydration, especially under late-season drought. When drought occurs before anthesis varieties with a high stomatal conductance are preferred (Izanloo et al. 2008, Reynolds et al. 2001, Blum 1989). Among the varieties also significant differences were noticed (Table 6). Nevertheless, the stomatal conductance just showed few correlations and little significance among the varieties. This criterion might achieve better results during drought conditions.

For selecting productive candidates there is the need of an appropriate combination of different selection criteria. No progress in drought tolerance will be achieved with just one single selection method. Blum et al. (1981) stated that “The total drought resistance of a genotype cannot yet be defined physiologically and most probably it does not exist as a unique plant trait”. This assumption was confirmed within the results of this study. The earlier proposed issues (see 1.2) can be responded as follows:

- No correlations were detected among the novel selection criteria in the core set (Table 10).
- The interactions between the novel selection criteria and the stress indicators were significant (Table 11).
- The association between the novel selection criteria and the growth stages and plant morphology was significant (Table 12).
- Significant correlations were shown between the selection criteria and the yield and quality parameters (Table 13).
- Interactions among the stress indicators were significant (Table 14).
- The stress indicators were significantly associated with the growth stages and plant morphology (Table 15).
- Significant correlations were reported between the stress indicators and the yield and quality parameters (Table 16).

- The yield and quality parameters were significantly associated with the growth stages and the plant morphology (Table 17).

From year to year weather conditions change and also drought can vary in its timing, duration and intensity. Therefore these climate factors, especially water scarcity, are extremely unpredictable. Additionally, the plant's physiological responses to drought are complex and are mostly dependent on further biotic or abiotic stresses too. That is the reason why breeding for drought tolerant varieties is so difficult and proceeds that slowly. Although some indirect selection indices are detected there is still a lack of effective and reproducible criteria and more research is required.

6. ABSTRACT

The worldwide climate change is influencing agriculture in Central Europe. The extreme weather conditions like drought and heat often result in poor crop yields. In Austria it is especially the Pannonic region which suffers from drought damages on crops. Due to this background a research project has been set up in October 2009 which is called "Winter wheat cultivars maintaining high yield under environmental stress". The participating countries were Austria, Germany and Hungary. A field experiment arranged in a randomized lattice design with three replications was set up at three locations in the East of Austria. At all three sites a core set of 25 winter wheat varieties and a supplemental set with 72 genotypes was studied. The objective of this master thesis is to test and evaluate the novel selection criteria (chlorophyll content - SPD, canopy temperature - OTE, stomatal conductance - STO, osmotic potential - OSP and electrical capacitance of roots - EKA) for selecting drought tolerant genotypes and to determine their correlations to drought stress indicators, growth stages, plant morphology, yield and quality parameters. Significant genotype variability ($p \leq 0.05$) was noticed for SPD, OTE, STO and OSP. EKA did not show differences among the varieties. SPD seem to be an effective selection criterion whereas OTE, STO and OSP were considered as critical traits. Due to the fact that EKA showed a non significant genotype effect and high variations within the replications of one plot, it has to be seen as a critical selection criterion too. Nevertheless many significant correlations were detected with EKA and therefore further studies are required. Regarding the correlations it was determined that in the core set no associations among the novel selection criteria were found. Significant interactions ($p \leq 0.05$ and $p \leq 0.01$) were shown between the novel selection criteria and the stress indicators, the growth stages, the plant morphology, the yield and the quality parameters. Further correlations were noticed between the stress indicators and the growth stages, the plant morphology, the yield and the quality parameters. The yield and quality parameters were significantly associated with the growth stages and plant morphology.

7. ZUSAMMENFASSUNG

Der weltweite Klimawandel hat Einfluss auf die Landwirtschaft in ganz Mitteleuropa. Durch Wetterextreme wie Trockenheit und Hitze kommt es vermehrt zu Ertragsrückgängen bei Getreide. In Österreich leiden speziell die im pannonischen Klima liegenden Regionen an Schäden, die durch Trockenheit hervorgerufen werden. Aus diesem Grund wurde im Oktober 2009 ein Forschungsprojekt unter dem Namen „Winter wheat cultivars maintaining high yield under environmental stress“ gestartet. Die teilnehmenden Länder waren Österreich, Deutschland und Ungarn. Die Feldversuche befanden sich an drei Standorten im Osten Österreichs. Angelegt wurden sie als Gitteranlage mit dreifacher Wiederholung und pro Standort wurde ein Kernsortiment aus 25 Winterweizen Sorten, sowie ein zusätzliches Sortiment aus 72 Genotypen angebaut. Das Ziel der Masterarbeit war, die neuen Selektionskriterien (Chlorophyllwert – SPD, Oberflächentemperatur – OTE, stomatäre Leitfähigkeit – STO, osmotisches Potential – OSP und elektrische Kapazität der Wurzeln - EKA) zum Thema Trockenheitstoleranz zu testen und zu bewerten. Weiters wurden Korrelationen zu Stressmerkmalen, Entwicklungsstadien, Pflanzenmorphologie, Ertrag und Qualitätsparametern bestimmt. Signifikante genotypische Variabilität ($p \leq 0,05$) wurde für SPD, OTE, STO und OSP festgestellt. EKA zeigte keine genotypischen Unterschiede. SPD konnte als effektives Selektionskriterium gewertet werden. OTE, STO und OSP jedoch sind als Selektionskriterien sehr kritisch zu betrachten. Da EKA keine genotypischen Unterschiede zeigte sowie eine hohe Grenzdifferenz aufwies, muss dieses Merkmal ebenfalls kritisch betrachtet werden. Trotzdem konnte man viele signifikante Korrelationen mit EKA aufzeigen und daher ist weitere Forschung nötig. Bei den Korrelationen wurde nachgewiesen, dass im Kernsortiment kein Zusammenhang zwischen den neuen Selektionskriterien besteht. Signifikante Beziehungen ($p \leq 0,05$ und $p \leq 0,01$) zeigten sich aber zwischen den neuen Selektionskriterien und den Stressmerkmalen, den Entwicklungsstadien, der Pflanzenmorphologie, dem Ertrag und den Qualitätsparametern. Weitere Korrelationen wurden zwischen den Stressmerkmalen und den Entwicklungsstadien, der Pflanzenmorphologie, dem Ertrag und den Qualitätsparametern festgestellt. Der Ertrag und die Qualitätsparameter waren mit den Entwicklungsstadien und der Pflanzenmorphologie signifikant korreliert.

8. REFERENCE LIST

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11.APENDIX - TABLES

Table A 1: Table of variance F values of the novel selection criteria (supplemental set)

Factors	Dependent Variables									
	SPD		OTE		STO		OSP		EKA	
Variety	*	34.10		1.27	*	1.85		---		0.13
Location	*	184.37		---		---		---		---
Variety/Location	*	3.44		---		---		---		---

* = significant at a level of $p \leq 0.05$

Table A 2: Table of variance F values of the stress criteria (supplemental set)

Factors	Dependent Variables							
	BLRO		SZF 1		SZF 2		SZF 3	
Variety	*	4.09	*	16.23	*	3.15	*	3.65
Location		1.79		1.13	*	74.25	*	73.50
Variety/Location	*	2.06	*	1.37		1.10	*	1.99

* = significant at a level of $p \leq 0.05$

Table A 3: Table of variance F values of the growth stages and plant morphology (supplemental set)

Factors	Dependent Variables							
	DTAE		DTBL		DTGR		WHOE	
Variety	*	29.28	*	30.58	*	8.40	*	18.88
Location	*	5182.01	*	8356.07	*	1565.49	*	537.22
Variety/Location	*	1.74	*	2.21	*	1.54		1.03

* = significant at a level of $p \leq 0.05$

Table A 4: Table of variance F values of the yield and quality parameters (supplemental set)

Factors	Dependent Variables									
	BEST		KOEQ		HLGW		TKGN		RPRT	
Variety		---	*	4.68		0.89		---		---
Location		---	*	1357.24		1.11		---		---
Variety/Location		---		---		---		---		---

* = significant at a level of $p \leq 0.05$

Table A 5: Electrical capacitance values (in nF) of the 25 varieties in Breitstetten

Variety	nF
GK Fény	0,48
Exklusiv	0,43
GK Kalász	0,38
GK Rába	0,33
Tacitus	0,33
Komarom	0,28
Hybred	0,27
Bitop	0,26
Tiger	0,25
Robigus	0,23
Pegassos	0,23
Brilliant	0,23
Hyland	0,23
GK Csongrád	0,23
GK Szala	0,21
Eurofit	0,21
GK Hunyad	0,21
Premio	0,20
Eurojet	0,19
GK Petur	0,17
Element	0,16
JB Asano	0,16
Capo	0,15
GK Békés	0,15
Midas	0,14