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Optimized winter wheat production in Kiev region of Ukraine

– A case study on cultivation properties and management focusing on sowing date and nitrogen fertilization

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Cover: Winter wheat, variety Skagen in Berezan (Ukraine). Photo Mats Magnusson, 2014.

Foreword

This Master's thesis comprises 30 credits as part of exam in the agriculture programme – soil and plant sciences, and was performed at the Department of Soil and Environment, Swedish University of Agricultural Sciences. The supervisor was Johan Arvidsson.

We want to thank the Board and former employee Jens Bruno at Grain Alliance who gave us the opportunity to conduct this thesis, and a great thank to our contact person on Grain Alliance Charlotte Claesson. We also want to show gratitude to important staff in Berezan, Ukraine, Evgeniy, Andrey and Maxim, who helped us with everything from transport, translation and giving us important information. Especially we want to thank our supervisor Johan Arvidsson, who devotedly supervised us and always was available for help and encouragement.

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Abstract

Ukraine is the tenth largest wheat producer in the world but average yields are low, about 3 ton ha^{-1}. A better understanding of growth conditions and factors limiting yield is important in developing strategies to increase grain yield. This Master's thesis examined the conditions for winter wheat cultivation (Grain Alliance strategy) in Berezan in the Kiev region of northern Ukraine, and the potential to increase crop yields. The wheat cultivation in seven nearby fields in Berezan was compared with one reference field in Uppsala in Sweden. The effect of sowing date was studied by determining plant development and growth in fields with different sowing dates. The effect of fertilization level was also studied in these fields. In the sowing date trials, the factors plants per square meter in late autumn and spring, shoots per plant in late autumn and spring, and plant weight in late autumn were measured. The yield-forming factors ears m^{-2}, kernels per ear, grain size and grain yield were also measured. In the fertilization trials, only grain yield factors were measured. To determine the growing conditions the soil physical properties and water availability were measured. The development of the winter wheat was also simulated by a phenology model with data from local weather stations.

The climate in Kiev is 3-5 ˚C warmer than for Uppsala during the period April-August. It results in more rapid plant development in Kiev compared with Uppsala and 4-5 weeks earlier maturity. Precipitation and evapotranspiration are higher in Kiev than in Uppsala. Soil conditions in the Kiev region are favourable, with good soil aeration and low bulk density combined with relatively high amounts of plant-available water. A normal year the amount of precipitation and soil water storage is adequate to supply the wheat with water and avoid drought on both the clay soil in the field in Uppsala and the silty loam in the fields in Kiev. The relatively high temperature and availability of water motivates a cultivation strategy with relatively high ear densities to achieve high yield, as ear size can be reduced by rapid plant development. If winter wheat is sown during the first 2-3 weeks of September there are good opportunities to use relatively low seed rates, as lower plant number can be compensated by tillering. If sowing is postponed quite high seed rates are justified.

The early-sown winter wheat in this study had significantly greater biomass and tillering in autumn than late-sown wheat. Plant number was higher for late sowing dates, depending on higher seed rates. Both early- and late-sown wheat survived winter very well. Plant stand density was high in all the seven fields in Berezan, much higher than in the reference field in Uppsala. There was a large reduction of tillers in spring, but final number of ears was still relatively high. As variety and seed rates varied between trials with different sowing dates, it is not possible to claim significant effects of grain yield depending on sowing date. Kernel size was normal but ear size was relatively low, and was the yield factor with highest correlation to yield level in the different fields.

Yield level was generally high, even in treatments with low fertilization, and yield increases for high fertilization rates (above 160 kg N ha^{-1}) were relatively low. This indicates quite extensive mineralization from the soil. No significant difference in yield level was found

between wheat fertilized with equal amounts of nitrogen applied in autumn and spring compared with spring only. From a crop perspective, nitrogen from fertilizer must be available at the beginning of stem jointing, when the need is highest. By dividing the fertilization into 2-3 application occasions from early spring to heading, it is possible to adjust the nitrogen rate to development and growth conditions to match stand requirements.

The Grain Alliance cultivation strategy gave considerably higher winter wheat yield than the average for the Kiev region, probably due to more intensive management, with the crop not limited by fertilizer deficiency or plant protection problems. Using varieties that combine hardiness and high yield potential, establishing plant stands of sufficient density and performing field operations, for example sowing and fertilization, at the right time are issues to work with for further improvement of winter wheat yield in Ukraine.

Populärvetenskaplig sammanfattning

Värme sänker höstveteskörden i Ukraina

Bra jordar och relativ gynnsam nederbörd gör Kiev-regionen i norra Ukraina till ett jordbruksområde med goda förutsättningar för växtodling. I höstveteodling begränsas dock kärnskördens storlek framförallt av en kort period av tillväxt och mognad till följd av hög temperatur under vår och sommar.

Ukraina är ett av de länder som odlar störst areal höstvete i Europa, näst efter Ryssland och jämbördigt med Frankrike. Skördenivån är däremot generellt låg, med dryga 3 ton i genomsnitt. Om skördenivån för vete i Ukraina kan höjas påverkar det den globala spannmålsmarknaden, men är särskilt betydelsefullt för Ukraina och det ukrainska folket som är beroende av jordbruksproduktionen och export av spannmål. Detta arbete har utförts som en fallstudie för att undersöka höstvetets odlingsförutsättningar i Kiev-regionen i norra Ukraina, med särskilt fokus på faktorerna såtidpunkt och kvävegödsling.

Ukraina kännetecknas av inlandsklimat med relativt kalla vintrar och varma somrar. Landet är stort och förutsättningarna varierar inom landet med mest värme och torka sommartid i de södra och östra delarna medan västra och norra Ukraina har något svalare somrar med klart mer nederbörd. Jordarna är lättbrukade och naturligt bördiga, med god vattenhållande förmåga och stora rotdjup. Kalla vintrar kan skada höstvetet genom försämrad övervintring, särskilt vid kombination av sträng kyla och litet snötäcke vilket oftast inträffar i de södra och östra delarna av Ukraina.

Höstvetets såtidpunkt är av betydelse både för dess tålighet och övervintringsförmåga och dess möjlighet att bilda sidoskott under hösten. I fältförsök som utfördes i studien hade inte såtidpunkten någon betydelse för övervintringsförmågan, dock var förutsättningarna för övervintring mycket gynnsamma det aktuella året. Sorter med god vinterhärdighet och sådd runt 20 september bedöms ändå vara av stor betydelse för att uppnå väletablerade plantor på hösten och en stabil och hög skörd över år. Tidig sådd gav i försöken betydligt kraftigare plantor med fler sidoskott på hösten. En generellt mycket hög utsädesmängd bidrog till att skillnaden i slutgiltigt axantal per yta inte påtagligt varierade mellan olika såtider då alla bestånd var mycket täta. Med denna höga utsädesmängd (310-370 kg/ha) utnyttjades inte höstveteplantornas potential till sidoskottsbildning och betydligt lägre utsädesmängder skulle kunna användas, särskilt vid tidig och normaltidig sådd.

Kärnskörden byggdes upp av ett relativt stort antal ax per yta och normal kärnstorlek (tusenkornsvikt), men med små ax. Det fanns tydliga skillnader mellan olika studerade fält, där de olika vetesorter som odlades bedöms vara den faktor som var av störst betydelse för variationerna. Att få större ax är därmed en nyckelfaktor för att nå höga skördenivåer. Mycket höstvete i Ukraina begränsas av en alltför låg kvävegödsling. I den studerade odlingen gödslades vete relativt intensivt och ett tillskott av kväve utöver generella gödslingen om 160 kg N ha^{-1} gav inte någon merskörd. Skördenivåer på 5-7 ton/ha vid så låga gödslingsnivåer som 50 kg N ha^{-1} antyder också på en betydande mineralisering från marken.

Torka kan vissa år utgöra en begränsning i höstveteodlingen i Kiev, men var det inte under odlingsåret 2014 och bedöms inte vara det huvudsakliga skälet till låg skörd. Även om skördepotentialen är lägre i Ukraina än i Västeuropa finns goda möjligheter att öka skörden genom väl anpassad gödsling och växtskydd, användning av mer högavkastande sorter samt god etablering för att få vitala plantor och lagom täta bestånd.

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1 Introduction

1.1 Background

Winter wheat is the largest cereal crop in both Sweden and Ukraine. For the past 10 years, winter wheat has been grown on approximately 300 000-350 000 ha in Sweden and 6 500 000-5 500 000 ha in Ukraine, which is about 11-14% of total Swedish arable land and 17-20% of Ukrainian arable land area (FAOSTAT, 2015). Under Soviet rule (1990), Ukraine was the fourth largest wheat producer in the world after US, China and Canada (FAO, 2015). However, production in the current situation has declined to about half and during 2013, Ukraine was in tenth place in the world, with production of 22.8 million ton. However, even if the production has been halved, it is more than 12 times the 1.87 million tonnes Sweden produced in 2013 (FAOSTAT, 2015) (Figure 1). However, despite the fact that Ukraine is one of the world´s largest wheat producers and has access to what often is referred as some of the world´s best agricultural land, the 10-year average is under 3 ton ha^{-1}. This can be compared with Sweden´s 10-year average of nearly 6 ton ha^{-1}, which is almost double the Ukrainian average (FAOSTAT, 2015) (Figure 1). The grain yields produced by western-owned agriculture companies in Ukraine are often higher than the average in Ukraine, but are still lower than the Swedish average. With this in mind, it is easy to imagine what great potential Ukrainian wheat cultivation may have and this was one of the reasons why this study was initiated. In this study, the main aim was to gather enough general knowledge of winter wheat to make qualifying statements on why the yield potential may differ between Ukraine (Kiev region) and Sweden (Uppsala region). Factors focused on were sowing date, nitrogen fertilization and how the different yield components contribute to final yield. The intensity of winter wheat cultivation in Ukraine was measured based on a Swedish-owned agriculture company’s (Grain Alliance) cultivation strategy, which corresponds well to intensive Swedish wheat cultivation management.

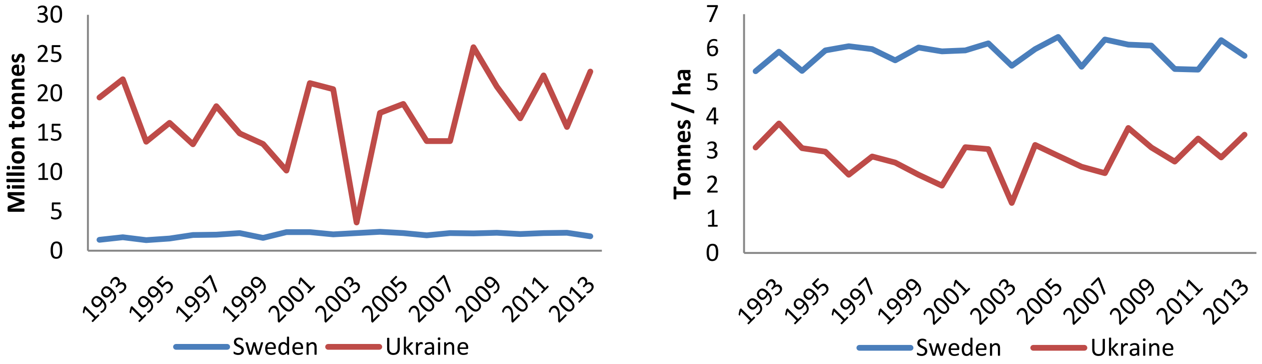


Figure 1. Left: total wheat production per year for the two countries; right: wheat grain yield per hectare in Ukraine and Sweden (FAOSTAT, 2015).

1.2 Objectives

The objective of this Master's project was to study winter wheat production in the Kiev region of Ukraine, with the focus on the influence of sowing date and nitrogen fertilization level on plant stand structure and yield levels. Site-specific conditions such as climate and soil properties were compared between Grain Alliance cultivation in Berezan in Ukraine and Swedish winter wheat cultivation in Uppland. Theories of wheat crop stand structure and development under different climate conditions and cultivation measures was studied in a literature review. The theoretical part of this report is relatively extensive, partly because it will provide a better understanding of winter wheat growing to the company Grain Alliance that commissioned this work, partly be able to put the results of a single year trials in perspective to other possible conditions.

Field studies with varying sowing dates and nitrogen fertilization levels were conducted in Grain Alliance winter wheat fields to get specific experimental data from the company's winter wheat cultivation in the Kiev region in 2014. A phenology model for winter wheat used to assess the influence of temperature in different growth stages for winter wheat grown in Berezan and Uppsala. General principles of different winter wheat management strategies under Ukrainian and Swedish growing conditions were discussed in relation to theory and applied to the results from the trials conducted in this study.

General objectives for the study of winter wheat in Berezan were:

- What are the climate conditions and how do they affect winter wheat cultivation?
- What are the soil physical properties and how do they affect winter wheat cultivation?
- What is the potential water supply during the growth season, according to climate and soil conditions?

Specific objectives for the study of winter wheat in Berezan 2013-2014 were

- Does the sowing date have any effect on the overwintering ability for winter wheat?
- How does the sowing date affect plant stand development and yield potential under given growing conditions?
- Does additional nitrogen fertilization increase grain yield according to the Grain Alliance fertilization strategy?
- How do different yield components contribute to final grain yield?
- Is there a palpable deviation between estimated yield potential in nationwide crop growth models and actual measured yields? If there are differences, what factors mainly explain possible deviations between models and actual yields?

2 Background theory

2.1 Stand development factors and yield components

2.1.1 Development of winter wheat

The life cycle of winter wheat can be described by growth and development, processes which occur more or less simultaneously throughout the wheat plant's life cycle. It is therefore important to be able to distinguish between growth and development when describing plant changes, especially when the plant growth stages overlap each other, for example when some part is developing and growing and another part is reduced or dying (White *et al.*, 2008).

Development is when the plant changes qualitatively, mainly in terms of number of organs, and growth is when the plant increases substantially in volume, area or mass (Fageria *et al.*, 2006). To accurately and conveniently describe the different developmental stages of cereals, the decimal scale of Zadoks *et al*. (1974) is often used.

Environmental factors affect to varying degrees the growth and development of the wheat plant. Examples of factors that affect plant development are temperature, day length, light intensity, nutritional status and various farming operations (Fageria *et al.*, 2006). The most important factor for development rate is the temperature, except in extreme situations, *e.g.* when the plant suffers from nutrient deficiency or drought. The relationship between minimum, optimal and maximum temperature differs for each development process (Porter & Gawith, 1999). Development can occur in a minimum range of 0-5℃ and the rate then increases linearly up to the optimum temperature range of 20-30℃ (Jame *et al.*, 1999). Higher temperatures lead to a reduced development rate and ultimately to a stop in growth, at around 40-50℃ (Porter & Gawith, 1999). Thermal time is often used to facilitate monitoring of plant development, which is often measured as degree days. This method is based on the fact that plant development cannot distinguish between time and temperature during the linear phase. For example, 2 hours at 16℃ have the same effect on development as 4 hours at 8℃. In practice, thermal time is often calculated from daily mean temperature minus a selected base temperature, which is the temperature when no development occurs (Hay & Porter, 2006).

It requires good knowledge of the different development processes to understand how the plant responds to different environmental factors and cultivation measures (Åfors *et al.*, 1988). The life cycle of winter wheat is usually divided into two phases, vegetative and generative. The transition between vegetative and generative phase occurs when the plant begins establish generative organs in the form of ears. Sometimes the life cycle is divided into three phases in which the third phase is the reproductive phase, which is the time after flowering/conception to the mature kernel (Åfors *et al.*, 1988).

The DC scale is very useful in both research and practical agriculture, since it makes it possible to get a good understanding of when for example it is appropriate to fertilize and apply chemical treatments to crops (White *et al.*, 2008). There are other developmental scales, such as Feekes and Haun, but in this study only the Zadoks decimal scale was used because it is widely used and accepted.

2.1.2 Yield components

It is preferable to divide the yield into three yield components in order to get better knowledge and understanding of how environmental factors and cultivation practices affect the assembly of the winter wheat yield. These are usually: number of ears per unit, number of kernels per ear and weight per kernel (Hay & Porter, 2006) (see Figures 2).

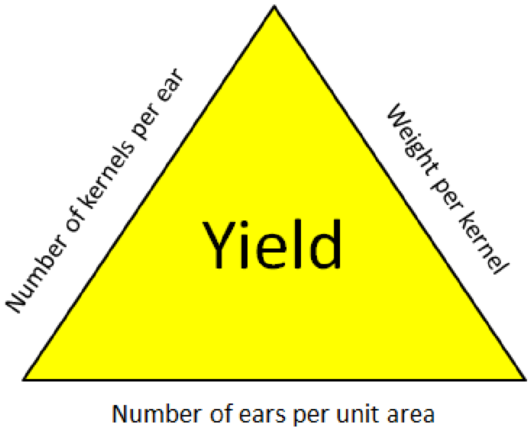


Figure 2. Yield triangle, the different yielding components determines how large the yield becomes.

The extent to which the various components contribute to yield depends largely on growing conditions and plant status during critical stages of development. Both abiotic and biotic factors affect these conditions but the establishment, formation and reduction of the components take place more or less simultaneously during the plant's life cycle. The three main components are relatively independent and therefore the relationship between them varies under different circumstances (Fageria *et al*., 2006).

What mainly affects the number of ears per unit area is the number of plants per unit area and the number of shoots per plant that become fertile. Number of kernels per ear is affected largely by the number of spikelets and number of flowers per spikelet that remain after conception and reduction (for illustration see Figure 3). The last yield component that affects the yield is weight per kernel, which is determined by the amount of assimilate that can be made available during the kernel filling phase (Hay & Porter, 2006). The construction of ears and spikelets is shown in Figure 3.

Figure 3. "Bristly" (awned) ears of wheat with a spikelet marked in red, from Berezan (Ukraine)

2.1.3 Sowing conditions and emerging frequency

A cereal kernel mainly requires moisture, oxygen and a suitable temperature to germinate. Germination starts when the kernel has absorbed moisture and reached a moisture content of at least 35-45% (Evans *et al.*, 1975). Problems with low oxygen levels are often associated with too high a concentration of water around the kernel. Poor oxygen supply limits kernel respiration, resulting in energy deficiency in the germinating kernel, and can cause poor germination or can in the worst case lead to kernel or seedling death (Fitter, 1987). Temperature has a major impact on germination rate. Winter wheat germinates in the temperature range 4-37˚C, but optimal temperature is between 12 ˚C and 25 ˚C (Spilde, 1989). During germination, primary roots and the coleoptile emerge. The coleoptile acts as a protective shell around the first true leaf as it makes its way up to the soil surface (Kirby & Appelyard, 1987). It stops growing as the first leaf emerges out of the tip (Fitter, 1987). If the moisture conditions are favourable, the time from sowing to emergence may vary between 100-150 degree-days at a sowing depth of 25-40 mm (Robertson *et al.*, 2004; Sylvester-Bradley *et al.*, 2008). Kernel size does not affect its ability to germinate, but a larger kernel has more resources for germination, resulting in faster establishment and larger seedlings (Moshatati & Gharineh, 2006). Under field conditions, large kernels give improved field emergence and a greater stand. The main reason for poor field emergence with small seeds is that small kernels have too limited energy reserves to cope with establishment under less favourable conditions (White & Edwards, 2008).

Achieving good emergence requires that the environmental conditions are as good as possible for the seed. Depending on soil type, tillage practices, water availability, weather conditions, etc. different strategies are required to achieve the best possible results in each specific location. The time of sowing should be adjusted based on the temperature to allow rapid germination and give the seedlings time to establish well before winter. Since winter wheat is grown on large areas under very varied conditions worldwide, varieties and cultivation strategies have to be developed based on each site’s characteristics. The time of sowing must also always be considered according to the availability of moisture. This is especially important in dry conditions and on soils that easily dry out in the seedbed, e.g. clay soils. Deeper seed drilling can be beneficial to ensure adequate soil moisture. If there is sufficient moisture in the seedbed, it is on the other hand better with shallow sowing to get faster establishment (Håkansson *et al.*, 2011). Creating sufficiently fine aggregate structure in the bottom of the seedbed is one way to achieve good moisture conditions around the kernel. Shallow soil reconsolidation after sowing also increases the contact between the kernel and soil, which facilitates water uptake by the kernel (Håkansson *et al.*, 2011). On many silt and silty clay soils there is a risk of crusting when rainfall is followed by rapid desiccation after sowing. The crust creates mechanical resistance for the coleoptile and affects its emergence, but the primary impact is often due to the limited aeration of the soil caused by the crust. A more uneven surface and coarse aggregate structure reduces the risk of crusting and is a reason to avoid intensive cultivation and soil reconsolidation (Baumhart *et al.*, 2004).

Field emergence of wheat generally ranges in the interval 70-90 % of germinable kernels sown. In poor seedbed conditions the emergence can be even lower. High temperature in the soil can cause damage or death of geminating seed or emerging plants and is another problem that may affect emergence rate in hot and dry climates (White & Edwards, 2008). A common cause of poor emergence is uneven seed placement, where kernels are placed either too deep or too shallow to successfully establish. Problems with low emergence rate because of uneven and coarse seedbeds are more common on clay soils than on loamy and sandy soils. Succeeding with good seed placement is due primarily to the previous seedbed preparation and the ability of the seed drill to maintain uniform depth. An uneven field soil surface, coarse clay aggregates or plant residues hamper the coulters placing all the kernels at an even and appropriate depth (Riley *et al*., 1994). Even kernels that are placed too shallow to get moisture from the seedbed might germinate if precipitation follows. However, with dry weather after sowing emergence is entirely dependent on the seedbed conditions and seed placement. If it is common for heavy precipitation after sowing, a sufficiently coarse structure of the seedbed is important to stimulate infiltration and reduce the risk of crusting on silt and silty clay. When a no-tillage system is applied continuously, compaction of the topsoil may arise if there is heavy traffic or traffic under wet conditions in the field. Compaction of the topsoil can adversely affect plant root development, and to some extent the soil’s infiltration capacity (Soane *et al*., 1978). No-tillage sowing may have other advantages in terms of a more even moisture distribution in the soil, less evaporation, lower soil temperature because of the stubble and plant residues that reduce the solar radiation on the soil surface. Plant residues and stubble also prevent snow drift and protect against severe cold. This is of particular importance in dry or cold areas (Robertson *et al*., 2004).

Late sowing results in poorer field emergence, as lower temperature gives slower germination and a higher percentage of grains that die as seedlings (Spink *et al*., 2000). An increased seed rate also reduces the establishment percentage because of increased competition between seedlings (Gooding, 2002; McKenzie, 2007). Sowing in good conditions is important and postponement of sowing is justified in, for example, unsuitable dry or wet conditions. Emergence rate of the seed varies due to the quality of the seedbed and the weather conditions for each year, so the seed rate should preferably be based on experience of farmer’s own growing conditions and cultivation systems. Counting winter wheat seedlings in some small plots of the field in autumn is a good way to compare the emerged number of plants in proportion to the number of germinable kernels sown.

2.1.4 Tillering

In general, winter wheat needs 100 degree-days to develop one leaf, but there can be some differences between varieties and growing conditions (Robertson *et al*., 2004). Soon after emergence, the winter wheat plant initiates tillers in the lower leaf axils. Normally the first tiller appears when the main stem has three leaves. The number of tillers that develops depends on the growing conditions, the duration of the tillering period and the plant density. Commonly the main stem can develop three primary tillers; these tillers may in turn develop secondary tillers, and the secondary may develop tertiary and so on (Fagaria *et al*., 2006). From the tillers, nodal roots are initiated and when they appear they are white and shiny, growing from the crown or sometimes lower parts of the plant above the soil surface (Kirby & Appelyard, 1987). In English field studies with low seed rates of early-sown winter wheat, plants had up to 20 fertile tillers. In general, 2-3 tillers are more common in the spring for stands with 200-300 plants m^{-2}. When stem elongation starts there is normally a further reduction of tillers (Spink *et al*., 1999). The potential number of tillers varies between varieties; semi-dwarf wheats have generally good tillering capacity (Baker and Gallagher, 1983). In general, however, tillering is most dependent on environmental conditions and temperature, radiation, water and nutrients, and especially the duration of growing conditions (Spink *et al*., 2000). Tiller formation and growth is sensitive to environmental and nutritional stress. It both delays tiller emergence and slows growth (Perry & Belford, 2000). Water deficit reduces tillering (Stark and Longley, 1986), and waterlogging has the same effect (Robertsson *et al*. 2009). There is also a positive correlation between nitrogen supply and tillering (McKenzie, 1998). The internal light competition between plants regulates the stand density and the production of tillers ceases when the fraction of Photosynthetic Active Radiation (PAR) exceeds a specific threshold (Evers *et al*., 2006).

The date of sowing has a great impact on the growing condition in the autumn. Longer days and higher temperature allow early-sown plants to grow and produce more tillers than later emerged plants (White & Edwards, 2008). The growth and development of roots is quite similar to the aboveground growth. A longer period of establishment in the autumn gives a stand with more aboveground biomass and roots (Perry & Belford, 2000). The larger number of tillers per plant in low plant density stands is determined by larger and more intensive tiller production under a longer period, but also by improved tiller survival (Whaley *et al*., 2000). An increase in radiation during the tillering period had a negligible effect of shoot number, but when applied during the period of stem erection it increased the numbers of ears m^{-2}. Increased temperature may affect daily growth positively, but the higher rate of development as a consequence of the higher temperature in general reduces the total growth of wheat (Thorne & Wood, 1986). Early-sown winter wheat can produce many tillers in both autumn and spring, but the reduction is extensive for spring tillers in dense stands during stem elongation. The response to grain yield from spring-developed tillers is therefore more important in late-seeded wheat and sparse stands (Thiry *et al*., 2002).

2.1.5 Hardiness, vernalization and winter survival

2.1.5.1 Winter stresses and hardiness

The winter survival ability of a wheat plant does not depend only on its ability to tolerate low temperature, but is a combination of response to winter stresses in the form of weather, soil conditions and cultivation practices that affect the plant's potential to survive (Fowler & Gusta, 1978).

The most common causes of winter kill are all directly or indirectly related to the low temperatures. Examples of directly related problems are: the lowest possible survival temperature for each variety; the plant has not initiated or accomplished its hardening process to withstand low temperatures due to late establishment or sudden temperature drop (Braun & Sãulescu, 2002); desiccation due to prolonged periods of cold and dry weather (Gusta *et al.*, 1997a); extended periods of low temperatures, especially below -15℃, leading to reversion of winter hardiness; and fluctuating temperature between freezing and thawing can lead to cell death due to ice formation inside the plant, especially when ice crystals are enlarged every new freezing interval (Olien, 1967). Ice formation around the plant or if it is covered by a layer of dense snow may also result in plant death. This happens mainly in areas with high precipitation and where freezing and thawing is common (Andrews *et al.*, 1974). In extreme cases, the formation of ice around the plant enhances the negative effect of lower temperatures because of the high thermal conductivity of the ice. It is more common for plants to be damaged by waterlogging with or without ice formation, which leads to suffocation because of low gas permeability, resulting in oxygen starvation (Poltarev *et al.*, 1992).

More indirect problems with low temperatures and snow are frost heave and snow mould. Frost heave arises due to ice formation in the soil surface at fluctuating temperatures, which can cause plant damage and death as the plant is pulled up and the roots are exposed or snap off. Snow mould is a one of a number of fungal diseases that can affect winter wheat. Problems with snow mould often occur with long-lasting snow cover (Braun & Sãulescu, 2002).

Many factors can cause winter kill but ice formation in plant tissue is generally the greatest problem. When a plant is exposed to temperatures below 0 ℃ it is exposed to dehydration. This means that there is water transport due to the cooling process of the plant from the cells into the spaces between the cells, resulting in permanent modification in the structure and metabolism. As long as the water freezes between the cells and the formation of ice does not become too strong, the plant will survive relatively well, but if the temperature drops suddenly the water will freeze inside the cell because there is too little time to transport it out. This will probably lead to cell death, since the ice mechanical pressure becomes too great and the cells break (Braun & Sãulescu, 2002).

To survive frost damage, the plant must induce the hardening process. Winter wheat is no more cold-resistant than spring wheat during the summer. The hardening process is induced by low temperatures and is genetically linked to metabolic processes requiring energy. Cold tolerance is not a static state, but varies depending on various factors such as time, temperature, day length, soil moisture and water content of the plant. Cold tolerance is variety-dependent and can vary greatly between different varieties (Åberg, 1974).

The hardening process is induced in two stages, the first stage as the temperature approaches 0 ℃ and the second when the temperature is around -3 to -5 ℃. During the first stage, sugars accumulate in the cells (vacuoles). This deposition increases the cell solution’s osmotic value, which lowers the freezing point. This accumulation correlates simultaneously with a change in protein synthesis due to a substantial increase in the hormone abscisic acid (ABA). During the second step, which is induced during freezing temperatures, there is a reversible change of the membrane composition. The result is that the water potential of the cell (parenchymatic tissue) can be further reduced (Sãulescu & Braun, 1988).

2.1.5.2 Vernalization

All winter wheat varieties require some kind of vernalization period to form generative organs. Vernalization is defined as the minimum requirement of chilling treatment of winter annuals to be able to flower (Chouard, 1960). The requirement of vernalization is critical for plants that are biannuals/winter annuals in areas with cold winters, to prevent the transition to the reproductive phase during the wrong season. To cope with cold periods in the winter and ensure that flowering occurs during the right conditions, winter wheat uses two mechanisms, vernalization and day length. Both these mechanisms are important for controlling the transition from the vegetative to the reproductive phase (Mahfoozi *et al*., 2001). When the vernalization requirement is saturated, the generative phase may begin and winter wheat gradually starts losing its cold resistance, even if the temperature is just above zero degrees. Interaction between vernalization and day length in late winter allows the plant to resist low temperatures better at shorter than at longer day lengths (Mahfoozi *et al*., 2001).

The vernalization requirement varies greatly between cereals but also between different varieties. This process is usually fastest when the temperature is just above zero, but optimal vernalization temperature is variety-dependent. Winter wheat plants go through vernalization in a wide range of temperatures, but the optimal range is between 0-11 ℃ and the length of the ‘cooling period’ required varies between varieties from 40 to 70 days. Vernalization may take even longer if the plant is exposed to a period of higher temperature (>18 ℃) due to de-vernalization (Robertson *et al*., 1996).

Vernalization can occur at different stages in the life cycle of winter wheat. Wheat can go through vernalization without actually germinating and emerging. It can in some cases go through vernalization when the kernel has absorbed moisture and swelled. This has been found to be the reason why winter wheat sown at different times can almost follow the same development rate later in the spring (Wikander, 1990).

2.1.5.3 Effects on the winter survival depending on autumn development

A general recommendation regarding the optimal sowing time for overwintering is that sowing (if the seed germinates directly) should be performed 4-6 weeks before the onset of winter (Fowler, 1982). Studies examining the optimal sowing depth for overwintering have demonstrated that shallow sowing (between 10-25 mm depth) is the most optimal, provided that there is enough moisture for germination and sowing is done during the optimal time (Loeppky, *et al*., 1989). The reason is that hardening (cold tolerance) is an energy consuming process and shallow sowing during the optimal time leads to rapid emergence. This ensures that the plant photosynthesis starts earlier and is able to store energy and produce at least three leaves and a well-developed crown, before the temperature starts to drop. A plant with this minimum development (DC 13) is prepared to initiate the hardening processes, but the optimal development stage is suggested to be when the plant has 1-2 tillers (DC 21-22) (Fowler, 1983). Even if a hardened plant does not grow during autumn and winter, it can still photosynthesize throughout the entire period, provided that the temperature is sufficiently high and the leaves are intact. This photosynthesis can contribute significant deposition of sugar that can be used as energy for crown/plant respiration (Savitch *et al*., 2002).

It is also important that sowing is not performed too early, as early sowing can lead to poor overwintering and reduced cold tolerance. Elongation of the apical meristem towards the soil surface due to an overgrown stand and fluctuating temperature may expose the crown to damaging cold (George, 1982). Early established seedlings can act as a green bridge, overlap, between newly emerged seedlings and volunteer wheat. Severe winter wheat diseases can be transmitted by vectors (insects) between infected volunteers and newly emerged plants (Fowler, 1983). Overgrown stands in early autumn increase the risk of various snow moulds, that can more easily spread between plants if they are overgrown and therefore to a greater extent in contact with each other (Murray, 1999).

The crown of the winter wheat plant develops between the soil surface and the kernel (Figure 4). If the kernel is planted at a depth greater than 40-60 mm, the internode between the first leaf and coleoptile will push the crown against the soil surface, within a range of 40 mm. From the crown nodes, tillers, leaves and the main root system develop. If the crown is damaged by frost or runs out of energy during the winter, the plant most likely dies (Kirby, 2002).

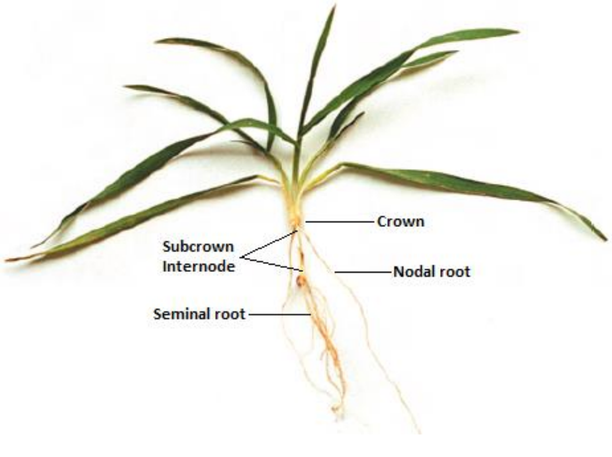


Figure 4. ***Illustration of a winter wheat seedlings root system. Based om photo from Allan Andersson, 2005.***

2.1.6 Adoption of sowing date and stand density strategies

Optimum date of sowing may vary depending on the weather conditions in each specific year and it is difficult to forecast the weather for the month following sowing. Recommended sowing date is usually based on studies of varying sowing dates over several years to get an average of years with different conditions. The number of final developed leaves and number of shoots increase with early sowing, both for high and low seed rates. The number of leaves is quite independent of seed rate, but the number of shoots is significantly higher for low seed rates **(**Spink *et al*., 2000). The optimum sowing date is not just dependent on plant density and development, but also on varying winter hardiness and susceptibility to diseases (Fowler, 1983).

The wheat plant's capacity to compensate for low plant densities is primarily based on its ability to produce tillers. Under very favourable climate conditions, the wheat plant is capable of compensating for extremely low plant densities. However, it requires early sowing and long periods of moderate temperature in autumn and spring to give the plant enough time for tillering (Gooding *et al*., 2002). Therefore, economic optimum plant density in areas with higher latitude may be expected to be greater, especially when sowing is postponed. However, many farmers could adopt a lower seed rate at early sowing date and utilise the wheat's potential for tillering to achieve a dense population (Spink *et al*., 2000). To optimize solar radiation efficiency, cereal plants should be arranged equidistantly from each other, but sowing techniques are based on row drilling, often with different distance between plants within rows and between rows (Chen *et al*., 2008). Numerous studies have demonstrated that grain yields are higher for cereals sown with narrow row spacing compared with wide (Marshall & Ohm, 1987; Johnson *et al*., 1988; Freeze & Bacon, 1990). The yield reduction tends to be greater for wheat when row spacing is increased under favourable conditions. The main reason for reduced yields with wide row spacing is limitation of spike density due to increased inter-row competition (Andersson, 1983).

The most suitable seed rate for a specific site and date of sowing depends on the level of plant density that is considered to be optimal, and then the seed rate must also be adjusted according to the field emergence and overwintering that can be expected. The optimal number of plants depends on several factors, and wheat's ability for compensatory growth is evident from the fact that yield levels tend to be similar across a wide range of seed rates (Spink *et al*., 2000). Seed rate for wheat varies globally, usually in the range 50-600 germinable kernels m^{-2}. There are in general two principles of seasonal patterns of water availability, either based on soil water storage or on precipitation during growth season (Ludlow & Munchow, 1990). If water availability is a major yield-limiting factor, the crop stand density should be adjusted according to water management, so there is water enough for grain filling. Dense stands threaten to consume plenty of water for vegetative growth. In dry areas where the wheat's water supply is primarily based on soil water storage, there is a great risk of it running dry prematurely and the grain filling may be strongly reduced if the stand is dense (Robertson *et al*., 2004). On the other hand, in areas with favourable climate and intensive cropping systems an increased plant density results in increased yield potential by more ears per m^2. This correlation holds for low to moderate plant densities (Spink *et al*., 2000). High plant density leads simultaneously to increased competition between plants, which affects every single plant’s opportunity for growth (Darwinkel, 1983). An increased number of plants per m^2 results in fewer fertile shoots per plant, reduced number of kernel per ear and lower individual grain weight (Darwinkel, 1978). In English studies, the effect of mutual shading became noticeable when the number of fertile shoots exceeded 400 m^{-2} (Spink *et al*., 2000). The ability to produce fertile tillers varies between different varieties, especially for tiller production in the spring. If winter kill is a common problem, it is important to use a variety that can compensate for low plant densities in the spring and produce a sufficient amount of ears. If stand density is generally sufficient in the spring, varieties with potential to produce heavy ears have the highest total yield potential (Yngwe, 2010).

A Ukrainian study showed that winter wheat sown on 10 or 20 September produced the largest yield for the growing season 2011-2013 (Melnyk *et al*., 2014). The numbers of ears per m^2 was highest for 10 September (400-500 ears per m^2), and decreased for every 10 days of delayed sowing, with the greatest reduction for 1 and 10 October. The number of kernels per ear was generally largest for sowing on 20 September (30,7-39,7 g 1000-kernel^{-1}). Low densities of fertile shoots (300-400 m^{-2}) due to late sowing were not compensated for by larger ears in the study (Melnyk *et al*., 2014). In Swedish studies the optimum date of sowing is in the range 10-20 September, with the earlier date for northern winter wheat areas and the later for southern. Optimum economic seed rate in Sweden is estimated to be 350-450 germinable kernels per m^2, with the highest rate in the northern growth zone and lowest in the southern (Andersson, 1983; Bengtsson, 1983).

2.1.7 Vegetative growth from early spring to jointing

When the temperature starts to increase in the late winter or spring, the wheat plants will respond by preparing to start growth again. This can be a critical time if thawing and freezing is common, especially if temperatures drop drastically when the hardiness is often weak (Gusta *et al*., 1997). If the requirements for vernalization not have been fulfilled before or during the winter, this is the first response of the wheat plant to mild temperatures after winter. The induced hardiness is often reduced during cold periods of the winter, but when temperatures increase in the spring there is also a dehardening process. Winter wheat varieties known as winter hardy usually have higher vernalization requirements, greater hardening and a less sensitive response to temperature and day-length for dehardening in the early spring. These varieties have a lower risk of frost damage in the late winter and spring but they start growth later in spring, which implies either delayed or intensified development, which is negative for yield potential. It is therefore no gain to use varieties with greater winter hardiness than needed (Fowler *et al*., 1981).

Development stage and conditions of plants after winter can vary a lot and therefore there are different needs and potential for early growth. Plants that are less developed in early spring will always be somewhat delayed during the growing season, but depending on the vernalization the difference is often limited to only some days at harvest. This is possible through the fact that the plants have been vernalized at the same or almost the same time

(Fitter & Hay, 1987). The result of this is however that the final leaf number (FLN) on the main stem is often reduced. When the temperature and day length requirements for floret initiation are fulfilled, no more leaves can be initiated and therefore less developed plants are often limited in time to initiate leaves in the spring compared with plants that already have some leaves (Wang *et al*., 1995). The sensitivity to photoperiod varies between different wheat genotypes but also between different growth stages of wheat. Wheat is generally a quantitative long-day crop, which means that the plants do not need a specific day length to induce flowering but that increased day length intensifies development processes (Major, 1980). Temperature also has a great effect on the rate of development, and even abiotic and biotic stresses may accelerate development, but this of secondary importance compared with day length and temperature. The interaction of day length and temperature in early spring affects the ability for tillering in the spring greatly (Hay & Porter, 2006). If temperature is moderate in early spring it can allow growth, while it takes long time to fulfil the requirements to induce ear development and stem elongation. On the other hand, a late cold spring and then a sudden temperature increase contribute to rapid development and short period for tillering and leaf induction (Bean & Duncan, 2011).

Moderate temperatures and relatively short day length prolong the period of leaf development and growth, the phyllochron, and result in bigger leaves, especially flag leaves (Mossad *et al*., 1995). High temperatures and long days have adverse effects on leaves and advance floret initiation (Evans *et al*., 1975). The day length is not altered for a specific date and site between years, but according to various start of growing seasons there can be some differences between years, especially in the beginning of the season. An early start of the growing season often gives a longer period of growth under moderate temperatures. It seems as though there is a memory of development intensity for different growth stages. In particular, if the period of vernalization to double ridge (see section 2.1.8) appears earlier in the season at shorter day length, the sensitivity to day length seems to decrease, while the opposite reaction occurs if double ridge appears at long days. Because of this, the duration of the development phases of double ridge to terminal spikelet and terminal spikelet to ear emergence is increased (Kirby *et al*., 1999). The spring growth is mainly important to create a sufficient dense stand and a well-developed plant canopy. When the apex reaches the double ridge stage the development of the reproductive organ, the spike, has begun. The double ridge stage usually correlates with the beginning of the intensive growth period of stem erection and node elongation (Hay & Porter, 2006).

Leaf Area Index (LAI, also known as Green Area Index, GAI) is a common way to describe the canopy of a plant stand. The value of LAI (GAI) is the ratio of the area of photosynthetic plant tissue per unit horizontal ground surface area (Chen & Black, 1992). Under favourable conditions and relatively high plant densities, the LAI is about 2 at the beginning of jointing (start of stem elongation). During the period from jointing to anthesis the LAI can increase to above 7, which corresponds to about to 0.1 LAI per day. If conditions are suitable to produce ears with many kernels, the plant density would be adjusted to optimize solar radiation use efficiency. The denser the stand and higher amount of leaf area, the more photosynthetic active radiation (PAR) intercepted. However, in dense stands the efficiency in terms of dry matter (DM) produced per amount of PAR intercepted (g DM MJ^{-1} PAR) is reduced due to competition and shading of plants (Gooding, 2002). For example when the LAI rises from 2 to 3 the light interception increases by 15%, and when the LAI rises from 6 to 7 the interception increases by only 2% (Sylvester Bradley *et al.*, 2008). Stresses can reduce the leaf expansion, especially nitrogen and water stress (Sylvester Bradley *et al.*, 2008). Dense stands transpire more water than sparse stands. The transpiration is mainly dependent on biomass rather than leaf area, but LAI and biomass are often well correlated and therefore an increase in LAI leads to more transpiration (Boogaard *et al.*, 1997). High temperature decreases the duration of the vegetative growth stage and reduces LAI through reduced tiller survival, lower number of leaves and decreased plant height (Acevedo, 1991).

How much PAR a canopy can intercept depends on the LAI and the formation of the canopy, often described according to leaf angle. The canopy extinction coefficient is often used to describe how much light a leaf can intercept and this often correlates to the leaf angle. A horizontal leaf has for example a coefficient of 1, while a leaf with a leaf angle of 60˚ upwards has a theoretic value of 0.5, as the leaf area towards the sun decreases and more light will bypass the leaf. For wheat, the value generally ranges from 0.3 to 0.7, with low values for erect leaves. Depending on the leaf angle, it requires LAI of 4-7.5 to achieve 95% PAR interception (Loomis & Amthor, 1996). With steeper leaf angles higher LAI is possible to reach, as more leaves get a sufficient amount PAR to survive. This is of particular importance in maize but also in wheat, where plant breeders have evolved cultivars with steeper leaf angle that allows higher plant densities and higher yields (Hay & Porter, 2006).

The LAI corresponds generally very well to the amount of nitrogen absorbed by the wheat stand (Hay & Porter, 2006). English cropping guidelines specify the correlation of nitrogen absorption and LAI to 36 kg per unit LAI (Sylvester Bradley *et al.*, 2008). A good supply of nitrogen stimulates LAI through increased leaf expansion but especially through higher tiller survival (Spierts & de Vos, 1983). Tiller death is common at jointing and the abortion is greatly affected by competition between plants, measured by the ratio of red to far-red radiation. High nitrogen content in the plant decreases the threshold for abortion and increases the number of surviving tillers (Evers *et al.*, 2006). The nitrogen accumulation can be very intensive during the period from jointing to anthesis and sufficient supply during this period is important for high tiller survival and ear formation. Splitting the nitrogen dose, so one part is applied in early spring and the other at jointing, is a common approach, especially in temperate climates, to not stimulate excessive growth before jointing but supply the stand during stem elongation and ear development (Spierts & De Vos, 1983). There is also an opportunity to adjust the amount of nitrogen for the second dose according to the growing conditions and stand development since the first dose.

Early-sown winter wheat has a more extensive root volume and root biomass in spring due to the extended growth in autumn (White & Edwards, 2007). The growth of roots also increases during the stem elongation phase, but is not as intensive as for the aboveground biomass. In areas with favourable growth condition and adequate water supply, the amount of biomass is very high compared with the amount of roots, approximately 15-20 ton aboveground biomass and 1 ton dry matter roots (Sylvester Bradley *et al.*, 2008). Wheat grown in dry areas may have more roots but especially lower amounts of aboveground biomass (White & Edwards, 2007). In soils with good structure, the wheat roots can grow to more than 2 m depth (Kirby & Appleyard, 1987). Commonly the root depth is restricted by either too high water content (high groundwater level) or too low water content, but the roots are also often restricted by unfavourable growing conditions such as high bulk density of the soil, chemical constraints etc. General growth rate of winter wheat roots in Great Britain is 12 mm day^{-1} in the autumn and 18 mm day^{-1} in spring. The root density needed for nutrient uptake is often higher than for water; this is connected to low diffusion capacity, as phosphorus in particular requires high root density (Sylvester Bradley *et al.*, 2008). Great root depth increases the amount of soil water and nutrients available. Tall varieties generally have a slightly more extensive root system than semi-dwarf and dwarf varieties. Including their higher heat and stress tolerance, tall varieties are most suitable for dry and hot conditions. Tall varieties are for example superior to semi-dwarfs under dry conditions with yield potential under 2000 kg ha^{-1} (Richards, 1992). The majority of the roots are located in the topsoil, with approximately 70% of total root biomass in the upper 30 cm (Sylvester Bradley *et al.*, 2008). Lower amount of available water can increase the root depth, but if the soil structure restricts root growth the root density in deep subsoil is often very low and all the water cannot be used efficiently. If the topsoil is dry the root growth increases in the subsoil (Barraclough *et al.*, 1989). In English trials fertilization stimulated root growth in all soil layers and increased the total root length by 30% (Barraclough *et al.*, 1991).

2.1.8 Ear development and anthesis

When the vernalization is fulfilled the apex stops initiating leaves and the ear is initiated when the requirements of thermal time are reached. Double ridge is a commonly described development stage when the initiated spikelets are visible as two ridges on the ear. This occurs when about 60-80% of the spikelets are initiated and the ear apex is about 0.5 mm (Hay & Kirby, 1991). During the period following after double ridge the differentiation of organs on the ear begins and new spikelets develops until the terminal spikelet stage is reached. As the terminal spikelet initiation (TSI) indicates the final number of spikelets, it is an important development stage, also known for sensitivity to high temperatures (Slafer & Savin, 1991). At terminal spikelet the ear is about 4 mm and the number of spikelets normally varies from 20-30 (Kirby & Appelyard, 1984). As mentioned, the development from double ridge to terminal spikelet is sensitive to temperature and heat can reduce the number of spikelets drastically. Studies of varying temperature during the period from reproductive initiation to terminal spikelet indicate an optimum temperature of 12 ˚C. The minimum temperature for this process is about 2 ˚C and the maximum about 22 ˚C not to get adverse effects on ear formation and final grain yield (Farroc *et al.*, 2011). Raised temperature increases the development rate per day, but decreases the duration of developing events, which generally reduces the amount of developed spikelets (Porter & Gawith, 1999). The terminal spikelet appears at the same time as the start of internode growth, which is the beginning of stem elongation (Rawson *et al.*, 1998).

During the stem elongation stage, also known as jointing, there is intensive plant growth and competition for partitioning of assimilates within the plant. The competing sinks of assimilates are the leaf unfolding and expansion, stem, sheath and root growth including accumulation of reserves, and ear development and growth (Hay & Porter, 2006). The partitioning of assimilates to different sinks (organs) is a complex process that is not fully identified, but two factors of importance are the strength of the sink in terms of capacity to store assimilates and the distance for assimilate transport from source to sink (Cook & Evans, 1978). For wheat grown under optimum conditions, ear formation during this period is only dependent on the plant's capacity to provide the ear with assimilates and the genetic capacity to induce a great ear. As mentioned, elevated temperatures decrease the duration of development stages but can also decrease the efficiency in photosynthesis. Even the period from terminal spikelet to anthesis is sensitive to elevated temperatures due to decreased duration of events and supply of assimilates, but also damage to organs and functions by high temperatures (Saini & Aspinall, 1982). This applies particularly as high temperatures increase transpiration and hence the risk of water shortage, forcing the canopy to reduce stomatal conductance and therefore efficiency of photosynthesis (Hay & Porter, 2006). For example the abortion of florets increases with high temperatures and above 30 ˚C the risk for sterility of pollen and extensive loss of grain production is very high (Fischer, 1980; Kase & Catsky, 1984). A temperature below 9˚C or above 31˚C is considered to be suboptimal during anthesis due to increased number of infertile florets (Russell & Wilson, 1994). According to Fischer (1985), the number of grains per ear decreases by 4% per 1˚C increase from a base temperature of 15-22 ˚C during 30 days prior to anthesis. High temperatures after anthesis do not affect the grain set as severely as before anthesis. In studies, exposure to high temperature more than eight days after anthesis did not affect the grain number or the grain mass (Stone & Nicolas, 1995; Stone *et al*., 1995).

Day length and solar intensity affect the photosynthesis and the potential growth. In the UK, the daily dry matter (DM) production in the period May-July can vary from 0.1 to 0.25 ton DM day^{-1}, with the lower production on cloudy days and the higher on sunny days (Sylvester Bradley *et al*., 2008). Studies of the correlation between grain yield and different plant stand features confirm a clear connection between yield level and grain population density (kernels m^{-2}). The grain population density is also correlated with the biomass at anthesis, but the yield can only be predicted if harvest index is stable and not affected by yield reducing events during anthesis and grain filling and if harvest index is equal between cultivars (Moot *et al*., 1996; Bindi *et al*., 1999). By measuring the weight of ears at anthesis, the grain yield can be quite well predicted if there is no limitation of grain filling. Fisher (1985) suggested that 10 mg ear DM weight is needed for each surviving floret as a viable rule. The introduction of dwarf genes in wheat cultivars in the 20th century is one of main plant breeding actions that has increased the yield potential through higher harvest index and increased tolerance to intensive fertilization, as shortened stems decrease the risk of lodging (Slafer *et al*., 1994). The higher yield in semi-dwarf wheat cultivars is primarily achieved through higher grain population density, mainly due to increased number of kernels per ear (Allan, 1986; Slafer & Miralles, 1993). Some studies also report high significance for higher number of fertile shoots in semi-dwarf cultivars compared with standard height cultivars (Allan, 1986; Brandle & Knott, 1986; Fischer & Stockman, 1986). The common understanding is that the increased grain number per ear is due to the decreased competition for assimilates between ear growth and stem growth rather than an effect of more competitive ear partitioning in semi-dwarfs and dwarfs. When large ears are produced it is common that the kernel size in the distal spikelets (in top and bottom of the ear) is decreased. This can be viewed as decreased 1000-kernel weight and is not necessarily due to insufficient grain filling, but also limited storage capacity in less developed florets in the distal spikelets (Hay & Porter, 2006).

The grain yield of cereals is, as mentioned before, based on the harvest factors ears per m^2, kernels per ear and weight per kernel. Depending on the condition for growth and development, the rate of each factor may vary. Thus, one great issue in plant physiology has been to study what limits the yield in terms of source and sink. Limiting by source means that there is not enough assimilate produced in photosynthesis to supply the ear for maximum growth and grain filling. Limiting by the sink means that the potential for storage of assimilate is limited by the number of kernels initiated and the grain filling capacity (Hay & Porter, 2006). Evans (1993) concluded that this approach is, in general, not appropriate because source and sink are not independent. For example the ear (sink) is constructed of assimilates and nutrients from the plant (source) and the sink is therefore dependent on the source. However, even if there is a close interaction between the source and sink, the approach can still be used in discussions of yield potential and yield components. English studies with a great number of different winter wheat varieties grown under favourable conditions show that individual grain weight is the yield component with the lowest coefficient of variation (Gales, 1983). When the two yield components ears per m^2 and kernels per ear are combined to grain population density, kernels per m^2, this measure correlates very well with grain yield, while individual grain weight tends to be quite similar for different grain population densities. The consensus is that in the absence of stress, the yields of cereals is limited by the sink in terms of kernel population density (Fisher, 1985; Hay & Walker, 1989; Egli, 1998). However, the formation of ears and florets is dependent on events during the period from early ear development until anthesis, which is restricted by the source of assimilates and nutrients during this period. Studies of conditions and events effecting ear formation and anthesis have produced a substantial amount of evidence supporting the theory that in the absence of stress and other factors affecting grain set, the cereal grain yield is source-limited (Hay & Porter, 2006). If the number of spikelets and florets per spikelet is considerably reduced during ear formation and anthesis, it often results in reduced grain yield and decreased harvest index. In areas with drought stress, harvest index (HI) <0.30 is common, while HI can be above 0.6 for cultivars with high yield potential grown under optimal conditions (Boogaard *et al.*, 2012).

2.1.9 Grain filling

When the anthesis is over, fertilized ovules start cell differentiation and growth to produce germinable kernels, commonly known as grain filling. The potential grain size is dependent on the numbers of cells produced per fertilized floret (Wardlaw & Wallenbrink, 2000), but the actual grain size is dependent on the deposition of assimilates in the kernel, grain filling. The duration of the grain filling period is mainly dependent on temperature (Wiegand & Cuellar, 1981). In one study an increased temperature from 20 ˚C to 25 ˚C during grain filling decreased the duration of the grain filling period by 12 days (Yin *et al.*, 2009). Estimations from a number of studies show that for every 1 ˚C temperature increase above the optimum of 15-20 ˚C, the duration of grain filling is reduced by 2.8 days (Streck, 2005). The increased grain filling rate per day connected to higher temperature can compensate for the decreased duration of grain filling, but the yield levels are usually reduced when temperatures rise over the optimum (Stone *et al*., 1995). The period of grain filling is generally less sensitive to high and low temperature than the events of ear formation and anthesis. Optimum temperature is about 15-22 ˚C for efficient assimilate production, but also for optimal function of enzymes involved in starch biosynthesis (Spiertz *et al*., 2006).

Grain filling is dependent on the plant's ability to supply the ear with assimilates, which is a function of photosynthesis capacity. The optimum temperature for biomass production in wheat stands is on average about 20 ˚C, but this is mainly the effect of optimum development rate rather than photosynthesis efficiency. Reproductive organs are more sensitive to elevated temperatures than vegetative and are one important reason for decreased yields at high temperatures (Todd, 1982). The efficiency of photosynthesis is drastically affected by temperatures above 35 ˚C and below 5 ˚C. Net photosynthesis is reduced by high temperatures, because of increased respiration (Hay & Porter, 2006). About 25% of the yield reduction in wheat grown under day and night temperatures of 30/25 ˚C compared with 21/16 ˚C during anthesis to maturity were attributed to increased respiration at high temperatures by Wardlaw *et al*. (1980). Even if the wheat plant is less sensitive to high temperatures during grain filling than in prior development stages, temperatures exceeding 30 ˚C are common in many wheat growing regions in the world during this period and may affect grain yield and quality markedly (Gibson & Paulsen, 1999; Wardlaw & Wrigley, 1994). In one study, a day with a temperature of 30-38 ˚C during grain filling decreased the photosynthesis rate by 40-70% on that day and it took four days after the heat shock for photosynthesis process to recover normal function. Grain yield is affected even by shorter periods of heat shock, but not dramatically if conditions overall for grain filling are favourable (Schapendonk *et al*., 2007).

High temperature is often not just a single issue but often also connected to water deficit as it increases transpiration and loss of water (Ludlow & Munchow, 1990). Severe water deficit reduces photosynthesis drastically as the stomatal conductance is reduced and hence CO_2 assimilation. Moderate water deficiency reduces CO_2 assimilation somewhat, but promotes high water use efficiency as the amount CO_2 assimilated per unit water transpired is increased (Hay & Porter, 2006). Apart from decreased photosynthesis rate due to limitation of transpiration, water deficiency might also lead to elevated leaf temperature and increased development rate of the crop. As the wheat plant senses the temperature of leaves and not air temperature to determine thermal time, reduced transpiration due to water deficit may reduce the duration of events (McMaster *et al*., 2009). Limiting plant stand densities through low seed rates and restrictive nitrogen fertilization are two strategies already mentioned to avoid adverse water deficit during grain filling. Another strategy trying to avoid water deficit and heat stress during anthesis and grain filling is choosing early maturing cultivars in order to decrease transpiration and bring forward the events sensitive to high temperatures. On the other hand, fast developing early maturing cultivars have lower yield potential if the growth conditions are favourable (Fischer, 1985). Improvements of the photosynthesis and transpiration processes (Monneveux *et al*., 2003), as well as enhanced storage remobilization (Blum, 1998) and more heat-tolerant cell division of endosperm and grain filling (Stone & Nicolas, 1995(2), are challenges for better yields in arable regions affected by heat and drought.

The yield potential after anthesis is mainly based on the grain population density, but the final yield level is also dependent on grain filling, as it affects the kernel weight (Hay & Walker, 1989). The concepts of source and sink are often used to define different kinds of yield limitation, although there is often a close connection between source and sink (Hay & Porter, 2006). Plant stands with high grain population densities will rather be source limited during grain filling as there is high potential for assimilate storage. Under favourable conditions for grain filling, the final grain yield is well correlated to the grain population density, but under unfavourable conditions there will not be enough assimilates to fill the kernels with starch and there will be low kernel weight (Egli, 1998).

After ear emergence when all leaves are developed, there is less competition between different sinks of assimilates. Until the need for assimilates for grain filling reaches its maximum, there is a period when assimilates can be stored as stem reserves (Hay & Porter, 2006). As grain filling progresses the need for assimilates increases. If photosynthesis does not produce sufficient carbohydrates, the plant starts to transfer the stem storage reserves to supply the ear (Palta *et al*., 1994). The amount of carbohydrates stored in the stem is connected to the amount of biomass. In English studies the maximum measured amount of soluble stem reserves was about 25-35% of total biomass. The amount of stem reserves peaks at late booting and then there can be some fluctuations until early grain filling when the reserves start to decrease. Taller cultivars do not necessarily have more soluble stem reserves and are not affected by chemical plant growth regulation (Sylvester Bradley *et al*., 2008). Under optimum conditions, assimilates from photosynthesis account for 90-95% of grain filling (Kobata *et al*., 1992). However, under heat or drought when the photosynthesis is reduced, the redistribution of stem reserves increases and accounts for 6-100% of grain filling assimilates (Blum, 1998). A sink limitation during kernel filling is mainly based on low grain population density but also potential grain size. If the number of kernels per ear is low due to *e.g.* pre-anthesis heat stress, it is still possible to produce kernels of full size even under less favourable growth conditions during grain filling. This is because of less competition for assimilates produced in photosynthesis, but also relatively large stem reserves compared with number of kernels. On the other hand, low number kernels per ear reduce potential yield, as the maximum individual kernel weight has a upper limit and there is therefore no gain for the plant to produce more assimilates during grain filling than the sink can store (Wardlaw & Wallenbrink, 2000). When grain population density is high, there is also a higher demand for assimilates and grain filling is more likely to be limited by assimilate supply restriction and lower decreased individual kernel weight (Hay & Porter, 2006).

2.2 Nitrogen as a growth and quality factor

2.2.1 Nitrogen effect on yield

Nitrogen (N) is one of the most important nutrients for achieving large biomass and, indirectly, high yield. One of the main reasons is that N is the foundation for formation of proteins and therefore also the key enzyme that determines the extent of photosynthesis.

What to expect from a specific amount of N fertilizer in terms of yield depends on the plants' total uptake of N, the variety's efficiency when it comes to construction and maintenance of the photosynthetic machinery, genetic biomass potential and proportion of the total assimilate allocated to the grains (harvest index; the ratio between grain yield and total biomass) (Lemaire & Gastal, 1997).

In most cropping systems, N is the most limited nutrient and N fertilization in these systems leads to increases in dry matter, grain and protein yield. Biomass and grain yield increase linearly with the amount of N fertilizer until the N effect wears off and a maximum is reached. Additional fertilization will only increase the protein content and even higher fertilization can lead to a decrease in dry matter and grain yield (Hay & Walker, 1989; Below, 1995). Numerous studies have demonstrated, mainly in intensive agricultural areas in temperate parts of the world, that the first thing that happens when a shortage of nitrogen occurs is a negative effect on wheat seedling canopy; reduced tillering, smaller leaves and reduced life span of leaves and tillers. When N deficiency is really serious, photosynthesis is also negatively affected (Hay & Porter, 2006).

It is important to remember when it comes to N deficiency that it differs from water scarcity, in the sense that N that has been collected by the roots stays in the plant. Nitrogen, in contrast to some other nutrients, may also be relatively easily released by degradation of certain compounds and tissues and can therefore be relocated to new organs if needed, during the different development stages of the plant (Hay & Porter, 2006).

Nitrogen status in a plant affect the final harvest index, but this varies considerably between different geographical areas of the world and the extent to which the N is limited, and in which period of the plants' life cycle that the nitrogen is limited. The same applies nitrogen harvest index (Hay & Walker, 1989; Hay, 1999); see more in section 2.2.4.

High yields are the result of resource capture and assimilate partitioning. The total biomass of the crop depends more on the total resource uptake rather than the actual resource utilization, especially during water or nutrient stress, with some exceptions. In intensive winter wheat cultivation, the amount of harvested biomass depends on the total amount of PAR the canopy can capture, which in turn depends on the amount of water that can be transpired by the plants. When it comes to the amount of nitrogen, the relationship is not as easy, but studies indicate that the total uptake of nitrogen has a greater impact than the actual nitrogen utilization (Hay & Porter, 2006).

2.2.2 Uptake of nitrogen

The uptake of nitrogen depends on a number of factors, but is partly due to the quantity of nitrogen available for the wheat at sowing, supplied in the form of fertilizers, or mineralized during the season and in some places even atmospheric deposition (Goulding, 1990). The quality of nitrogen is also relevant, because the wheat plant can only take up inorganic nitrogen in the form of ammonium and nitrate ions by the roots. The total amount of nitrogen that will eventually become available to the plant depends on climatic factors and cultivation measures. Climate factors affect the amount of mineralized nitrogen that becomes available through biological activity in the soil before and during the growing season, a process affected by soil moisture and soil temperature. Cultivation measures include not only those performed during the season, but historical cultivation measures also have a major impact on the quality and quantity of the organic material in the soil (Hay & Porter, 2006). A high-yielding winter wheat crop can contain 200 kg N ha^{-1} under good growing conditions, but the proportions from fertilization or from soil delivery vary significantly between years (Vaidyanathan, 1984).

There are five important factors that influence the potential nitrogen uptake for a crop in fertile soils: crop root distribution in the soil profile, the root system’s adsorption capacity, N concentration in the soil and cultivation measures to maximize the availability of nitrogen and minimize losses. With a root density of at least 10 mm cm^{-3} the roots are able to take up all the available nitrate ions, while to adsorb ions from the soil water solution the roots have to be at a distance of a few mm from the ions (Bänziger *et al*., 2000). Studies have determined that the rate of uptake of nitrate is affected by the concentration of nitrate in the soil solution; increased concentration gives greater uptake (Forde and Clarkson 1998). Interception of ammonium and nitrate is possible through transport of the nutrients to the roots. Nitrate is mainly dependent on mass flow and ammonium on diffusion (Li *et al*., 2013).

In numerous field experiments, the degree of absorption of nitrogen has been found to match the growth of the crop, which in turn is determined by the amount of captured radiation (Justes *et al*., 1994). One approach that is used by crop modellers is based on positive feedback loop. The idea is that a large uptake of nitrogen (due to high ion concentration) offers an improved ability to absorb solar radiation due to larger leaves, which leads to increased growth rate and consequently a greater nitrogen demand and therefore greater uptake. Problem with approaches where the uptake is mainly driven by growth is that most crops have the ability to store gathered nitrogen in the tissues as organic nitrogen or nitrate (Millard, 1988). Devienne-Barret *et al*. (2000) have more recently proposed a combination of the different findings; with increased uptake at high ion concentration, biomass growth leads to enhanced uptake, but they simultaneously added an additional parameter that is based on the luxury uptake and deficiency. Generally, this new added parameter is based on a nitrate uptake index; if there a greater availability of nitrogen than the plant can take advantage of at the moment, a certain *extra* uptake can occur, which can then be stored in the plant.

In studies of winter wheat the nitrogen uptake during the period from sowing to start of stem elongation is on average about 30% (Sylvester Bradley *et al*., 2008) and 36% (Cui *et al*.,

2010) of the total nitrogen captured by the plant. The seasonal pattern of nitrogen might differ some between years based on growth conditions and factors as water stress, heat stress, diseases etc. A general pattern for nitrogen uptake in English wheat cultivation is 30% before first node detectable, 40% between first node and flag leaf appearance, 20% between flag leaf and flowering and the remaining 10% during grain filling (Sylvester Bradley *et al.*, 2008). According to this, there is no gain from a biological view of supplying large amounts of nitrogen at sowing in the autumn or in early spring, because the need for nitrogen is quite small. At the same time, the nitrogen should be applied in such way that a sufficient amount is available at the start of stem elongation. To get economical and environmentally sound fertilizer management, the nitrogen levels and conditions for application should also be adapted to reduce the risk of potential nutrient losses (Cui *et al.*, 2010). The main part of nitrogen fertilization should be applied before jointing to achieve optimum yield (Lutcher & Mahler, 1988). As fertilizer granules or liquids have to be dissolved and infiltrate the soil before becoming available for the roots, a sufficient fertilization effect is dependent on precipitation or high soil moisture if the fertilizer is incorporated into the soil (López Bellindo & López Bellindo, 2001). With excessive nitrogen levels compared with actual uptake, there can be significant amounts of residual nitrogen. Depending on climate and soil-related features, there can be a either a loss of nitrogen or an accumulation. Under Mediterranean climate conditions (Corbeels *et al.*, 1998), there are substantial carryover effects between years. This reduces the environmental issues with excessive fertilization in some years but increases the gain in testing the amounts of available nitrogen in soil at the start of each cropping season to adapt actual nitrogen rates to utilize soil reserves.

2.2.3 Nitrogen efficiency

The greatest impact on a plant’s nitrogen efficiency largely depends on how efficiently nitrogen is utilized in the plant's photosynthesis and the plant’s genetic distribution of structural tissues compared with grains (harvest index) (Hay & Porter, 2006).

The first thing that happens when nitrogen is taken up into the plant is that the largest part of the nitrate is converted to ammonium. The transformation takes place mainly in the leaf and stems, but can also to some extent take place in the root system. Storage areas for nitrate are often limited in both root and leaf cells (vacuoles) and the plant is quite sensitive to high concentrations of ammonium ion, as it becomes phytotoxic. The ions are therefore converted quickly to simple amino acids (glutamine and glutamate), which later serve as building blocks of more advanced compounds like pigments, nucleic acids etc.

Sinclair and Horie (1989) noted that ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) was the dominant nitrogen compound in various crops, corresponding to 50% of total soluble leaf protein in C3 species. Evans (1989) showed that the content of Rubisco in leaves had a linear relationship with the nitrogen content. By similar observations, assumptions have been made that this enzyme may be an important storage pool of nitrogen, in addition to the dominant position it has in photosynthesis (Huffaker & Peterson, 1974). There is a positive correlation between nitrogen content (Rubisco content) in individual leaves and their photosynthetic capacity but there is not the same clear correlation when studies are done on the complete plant canopy (Sinclair & Horie, 1989). It has been known for a long time that the architecture of the plant tends to ensure that the incoming radiation is distributed through the stand (Grindlay, 1997). Optimal foliage photosynthesis is achieved when the highest proportion possible of the incoming radiation is intercepted, which requires that the leaves are arranged in optimal positions relative to each other (photosynthetic apparatus exceeds its maximum and risks shade remaining leaf area). The growth is also maximized when the plant increases the nitrogen content of the uppermost leaves, which have the greatest potential to utilize most PAR (Field, 1983).

Ortiz-Monasterio *et al*. (1997) found a correlation regarding nitrogen utilization (quantity of biomass production per kilogram of nitrogen) and harvest index among newer and older wheat varieties registered by CIMMYT (international Maize and Wheat Improvement Center) between 1950 and 1985. In the study, they were able to demonstrate that one of the oldest varieties had the highest nitrogen utilization per kg nitrogen and one of the newest varieties had the worst. The main difference they found for was unfertilized trials (139 kg kg^{-1} N compared with a mean of 119 kg kg^{-1} N). This difference remained in the fertilized trials, but the difference was significantly less (93 compared with 86 kg kg^{-1} N). However, because of higher harvest index in newer varieties (0.43-0.45) compared with older (0.30), they gave a higher grain yield at moderate nitrogen rates. The study found that there was a difference between nitrogen utilization among different varieties but also that it was associated with a lower yield potential. This makes breeding and selection for this trait a lot more complicated.

2.2.4 Protein content

Apart from fertilizer management to achieve high yield, sufficient quality of the grain is also necessary to receive full payment. One important factor for bread quality wheat is protein content. The threshold value for bread quality is often around 11-13% of protein, which is approximately 1.8-2.1% of nitrogen content. Generally, there tends to be a negative correlation between quantity and quality for cereals and other crops (Hay & Porter, 2006). Simmons (1995) and Feli (1997) showed that there is a negative correlation between grain yield and its nitrogen content, with the yield varying because of different management actions (other than different fertilization levels) and environmental factors. It is still possible for farmers to achieve high yields and high nitrogen content, even if this correlation exists, but it requires the right amount of nitrogen fertilizer and timing.

The amount of nitrogen in the grains, which is mostly in the form of protein, depends on the crop’s nitrogen harvest index (distribution of nitrogen between grain and straw in the aboveground biomass) and its total nitrogen uptake. At grain filling two parallel deposition processes takes place, one with nitrogen and one with starch from existing biomass (leaves and stems), but grain filling is also dependent on current photosynthesis. During this phase allocation of the assimilates from photosynthesis prioritises the kernels, resulting in more or less starvation of the root system. Despite this, late ground application of nitrogen fertilizers can improve the nitrogen content in the kernel. The nitrogen content can also be enhanced by foliar application of urea (Wuest & Cassman, 1992; Bly & Woodward, 2003).

Trioi and Triboi-Blondel (2002) concluded that nitrogen and starch deposition in the kernels are independent processes and are affected differently by environmental factors. In winter wheat varieties, nitrogen harvest index is higher (typically >0.8) and less variable than harvest index (typically <0.6) (Löffler & Busch, 1982). The plant mobilizes all possible nonstructural nitrogen to the ears during and after flowering, a process less sensitive than the actual carbon deposition (harvest index). This process varies to a greater extent from year to year, depending on climate factors, stresses and management actions, and is therefore crucial for the varying protein content in the kernels (Hay & Porter, 2006). This is illustrated in a field trial by Gooding *et al*. (2002) where a varied seed rate and constant nitrogen fertilization (200 kg N ha^{-1}) resulted in a significant difference in biomass harvest but in an equivalent nitrogen uptake (Figure 5 next page). The difference in grain yield ranged from 6.8 to 8.6 ton ha^{-1} while the harvested protein content in the grains only ranged from 960 to 1060 kg ha^{-1}, corresponding to an increase of 25% compared with 10%. In the experiment, the negative relationship between quantity and quality was clear, with the increased harvest the protein content fell from 14 to 12.8%. In the same experiment in a trial with much higher nitrogen fertilization (350 kg N ha^{-1}), this level of nitrogen was high enough to counter the dilution effect and maintain the protein content of 14% for sowing levels. However the nitrogen harvest index declined with the increased fertilizer amount. This correlation has been shown by Wuest and Cassman (1992) in previous experiments, where nitrogen harvest index decreased from 0.8 to 0.6 with fertilization levels approaching 250 kg N per hectare. The basis for the dilution effect at increasing yields is that the total nitrogen content of the kernels is limited by the “source” and at a lower harvest, there are fewer and smaller grains (decreased “sink”) sharing the existing nitrogen and protein content increases (Marte *et al*., 2003).

Occasions when the protein content instead becomes higher due to smaller or fewer kernels depend on various environmental stresses and occur mainly during grain filling. High temperature together with water scarcity affects the deposition of starch to the kernels more negatively than the deposition nitrogen, providing a lower total yield, but with a relatively higher protein content (Bindi *et al*., 1999). Trials by Trioi and Triboi-Blondel (2002) have demonstrated that an increase in temperature during flowering of <20 to <30 ˚C resulted in a significant reduction in weight per kernel (27%) but the protein content was relatively higher (25%). Other experiments that examined the effect of drought stress during flowering have come to similar conclusions (Hay & Porter, 2006).

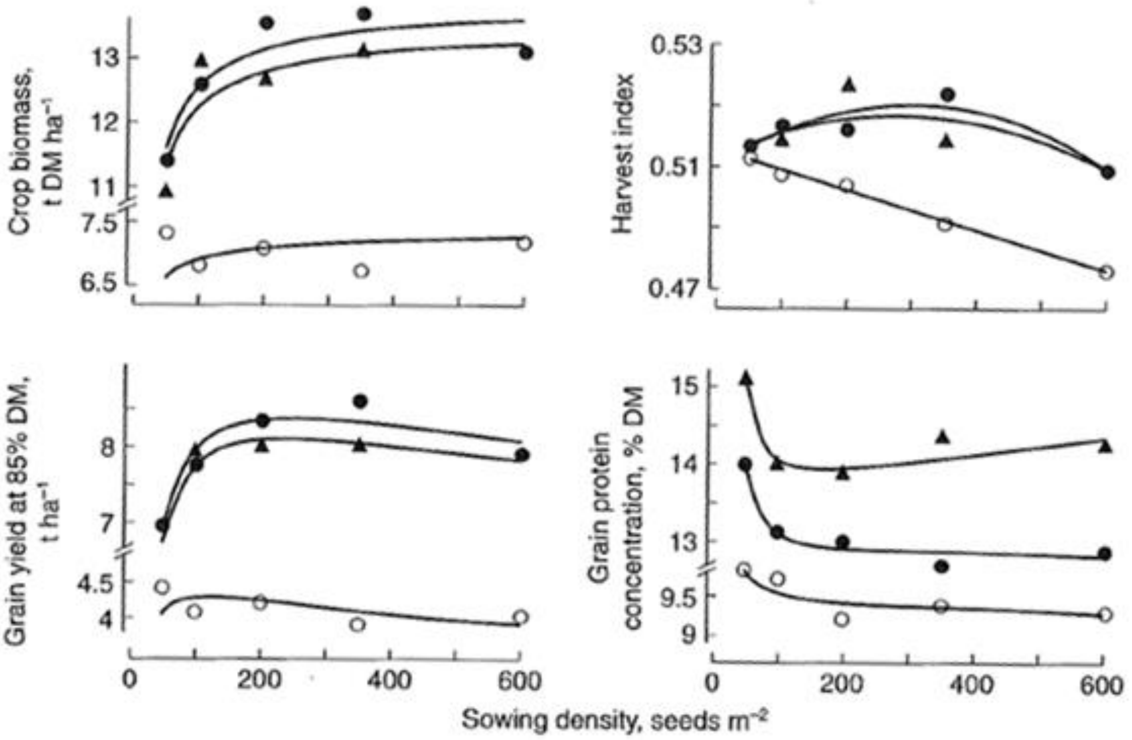


Figure 5. Illustration showing the effect of varied seed rate of winter wheat and a constant nitrogen fertilization of 0 (○), 200 (●) or 350 (▲) kg N ha^{-1} in trials from England by Gooding *et al*. (2002).

2.3 Factors affecting the timing and amount of fertilization

2.3.1 Nitrogen processes in the soil

Most of the nitrogen in the soil is found in the organic material and only a small proportion is in liquid soluble form, but since it is this form that the plant can absorb and utilize, it is usually that studied. The nitrogen in the soil is included in a recycling system where it can be both mobilized and immobilized. When organic material is degraded the mineral nitrogen is mainly released in the form of ammonium/ammonia (Havlin *et al*., 1999). Ammonium can either be taken up by the plant, adsorbed to soil particles or immobilized in organic matter, but also leached, but rarely in small quantities. Ammonium can be converted to ammonia and departs to the air, especially at high pH levels (Gezgin & Bayrakll, 1995) but also forms nitrate by bacterial processes. The amount of plant-available nitrogen and the proportions in which nitrate and ammonium occur in the soil depend on different soil and climate conditions and are not an accurate reflection of the fertilizers that might have been applied to the soil (Havlin *et al*., 1999).

Nitrate is not attracted to soil particles and is highly mobile in the soil solution (Dechorgnat *et al*., 2011). This makes it easily accessible for roots to take up, but can also easily leach from the soil profile in strong percolation *e.g.* after heavy rainfall (Hay & Porter, 2006). The rate of conversion of ammonium to nitrate (nitrification) is highest under conditions favouring nitrifying bacteria, which means neutral or high pH, good aeration of the soil, moist soil and relatively high temperature (Havlin *et al*., 1999). At hypoxic or anoxic conditions in the soil, such as due to saturation, there are bacteria that can reduce nitrate instead of oxygen, resulting in formation of mainly nitrogen gas (N_2), but also nitrous oxide (N_2O) and nitric oxide (NO) which departs to atmosphere (Arah & Smith, 1990).

Urea is a nitrogen compound that is not taken up by plant roots. In contrast, many soil organisms secrete urease, an enzyme that breaks down urea and which in contact with moisture forms ammonium and bicarbonate. Good access to enzyme in the soil, moisture and relatively high soil temperatures contribute to high conversion rate. Inadequate soil moisture on fertilisation with urea leads to high concentration of ammonium/ammonia and bicarbonate, which causes increased pH around the fertilizer and the risk of ammonia emissions (Havlin *et al*., 1999). High salt concentrations and high and low pH values are harmful for the plant, particularly for germinating and young seedlings. This means that fertilizer placement is important to avoid damage to the plant (Bremner, 1995). Good soil moisture contributes to faster diffusion of ions and more rapid equalization of concentrations, reducing the risk of injury associated with fertilization (Maddux *et al*., 1991).

Urea can be absorbed through the leaves of the plant, but when both the concentration of urea or ammonia, which is formed inside the plant after the uptake of urea, exceeds the critical concentrations it can cause necrosis (Bremner, 1995; Krogmeier *et al*., 1989). Liquid urea ammonium nitrate generally causes more leaf burn than other nitrogen fertilizers. Low to moderate temperature, relatively still air (windless) and high humidity favours the absorption of nutrients through the leaves and reduce the risk of severe burns and ammonia losses from urea through the leaves (Fagaria *et al*., 2009).

2.3.2 Application technology for liquid and granular nitrogen fertilizer

Ammonium nitrate (AN) or nitrate-based fertilizers are handled in granular form, and in winter wheat these fertilizers are primarily top-dressed on the soil surface in plant stands. Application takes place with either a centrifugal fertilizer spreader or a ramp spreader. If AN is incorporated into the soil it is usually through harrowing after broadcast fertilization before sowing, or alternatively side-dressed at sowing. The handling of urea is comparable to that of AN. Anhydrous ammonia is handled as a liquid by pressurizing it, but turns into a gas at normal atmospheric pressure and must be incorporated into the soil to be adsorbed in moist soil and form ammonium. Therefore, only techniques for incorporation of ammonia fertilizer exist. Urea ammonium nitrate (UAN) is a concentrated liquid nitrogen fertilizer, usually with a nitrogen content of 28-32% by weight. Of the total nitrogen, about half is in the form of urea, a quarter as ammonium and a quarter as nitrate (EFMA, 2000). UAN is usually applied with an agricultural sprayer where the solution is placed on the ground or crop, but similar machines as used for anhydrous ammonia can be used for application of UAN. Incorporation may also occur after spreading with an agricultural sprayer, by incorporation with tillage machinery. When application is done with agricultural sprayer, different nozzles can be used. If the aim of the nutrient solution is to infiltrate into the soil for the nitrogen to be taken up by roots, a dribble nozzle is appropriate (Grant, 2013). Advantages of drip application compared with spraying are that drops to a greater extent can be controlled to hit the ground in the presence of abundant plant residues. If fertilizer is placed on plant residues instead of the ground, there is an increased risk of ammonia emissions or nitrogen immobilization unless spreading is followed by rain (Keller & Mengel, 1986). If fertilization is meant to be foliar, *i.e.* with the intention of urea being absorbed by the leaves, a common spray nozzle can be used to get a more even application. Spreading with nozzles that provide atomized droplets or mist increases the risk of burns in general, but especially during later stage of development, mainly due to large leaf mass and high temperatures (Lutcher & Mahler, 1988).

2.3.3 Nitrogen application time

In the US in particular, use of ammonia is common, mainly due to its relatively low price, while the disadvantages lie in demanding management to prevent health/injury risks and the risk of nitrogen losses through ammonia emissions. Autumn application is common in areas with a continental climate (Vaughan *et al*., 1989). In comparison with autumn-applied ammonia, UAN is a worse option for application in autumn because the risk of nitrogen losses through leaching or denitrification of nitrate is greater for UAN (Grant, 2013).

For spring fertilization with nitrogen in growing crops such as winter wheat, there are, as mentioned, techniques for incorporating liquid ammonia and UAN. For fertilization in growing crops without incorporation, the application is done through broadcast topdressing or spraying of fertilizers. In English field trials simulating ammonia volatilization from urea, UAN and AN showed a significantly higher risk of nitrogen losses to the air from urea-containing fertilizers than when broadcast in winter wheat in spring. Average nitrogen losses through ammonia emissions were about 27% for urea and about 3% for AN, while UAN had an intermediate position. Variation in nitrogen losses for urea and UAN was great and the importance of weather conditions during and after the spread was clear. By adding urease inhibitor, ammonia emissions can reduce by approximately 70% for urea and 40% for UAN (Chambers & Dampney, 2009). On the other hand in a Canadian trial, fertilizing winter wheat with similar amounts of nitrogen from urea and UAN gave comparable yield to ammonium nitrate (AN), when applied in spring (Irvine, 2010). Most studies of UAN and urea-based fertilizers indicate better nutrient utilization when fertilizer is side-dressed compared with broadcast and incorporated into the soil by tillage. The higher ammonia losses can be explained by drier and more aerated soil after tillage, which reduces the soil’s capacity to diffuse water and bind the ammonia (Maddux *et al*., 1991.) Another reason for the deterioration in nitrogen utilization when urea-based fertilizers are broadcast and incorporated is immobilization of nitrogen in abundant plant residues. The amount of immobilized nitrogen with band application has proved to be significantly lower than with the broadcast application (Kelley & Sweeney, 2005). If urea or UAN is broadcast in growing crops under relatively warm and dry conditions, urease inhibitors have significant potential reducing ammonia emissions. However, the weather conditions during and after scattering (appliance) also have great effect. Heavier rain and cool weather after application may reduce the risk of ammonia losses markedly (Keller & Mengel, 1986).

Experiments in Idaho (USA) compared fertilization of winter wheat in the spring at different times with UAN and AN. The nitrogen was supplied at a rate corresponding to 100 kg N. Fertilization was conducted with a sprayer at the following stage of development (Zadok DC scale) for winter wheat: 22, 24, 26, 28, 31, 32, 37, and 43. In trials fertilized with UAN, some leaf burn occurred. Injury severity was clearly related to air temperature at application, with noticeable yellowing at temperatures above 14 ˚C. The trend for harvest outcome was clear, with early fertilization producing the highest yield, and yield declined continuously with fertilization during subsequent growth stages. No differences in yield level were found between UAN and AN widely circulated in the DC stage 22-31 (Lutcher & Mahler, 1988).

If fertilizer is to supply plants with available nitrogen when the plant needs it, application has to be done in sufficient time before the need arises so it can be degraded and transformed into plant-available form and dissolved and infiltrated into the ground to be available to the roots. This is particularly the case for the degradation of urea and nitrification of ammonium (Havlin *et al*., 1999). Nitrogen fertilization can justifiably be performed earlier than the required to ensure that the application can be performed based on the prevailing ground-bearing capacity. In dry conditions or with use of urea-based fertilizers, early dissemination also justifies dissolution of fertilizer and infiltration. A delayed fertilizer effect may otherwise cause reduce crop yield (Johnston & Fowler, 1992).

2.4 Climate conditions and soil properties

2.4.1 Climate in northern central Ukraine

Ukraine is divided into three agro-climatic zones. The southern half is classified as steppe, the western and north-western as plain (*polissya*) and the central and north-eastern parts as forest steppe (Kogan *et al*., 2013). The climate is temperate in the north-western part and semi-arid in the southern and eastern parts, with a transition between these both from west to east and north to south. The climate is characterized by cold winters and relatively warm summers. The Kiev region with the studied site in Berezan is in the north-central part of Ukraine with the forest steppe climate. During the 20th century the temperature increased, especially in the winter (Lapenis *et al*., 2008). The weather in the Kiev region is illustrated by the 30-year average precipitation and air temperature for the period 1961-1990 in Figure 6 on next page.

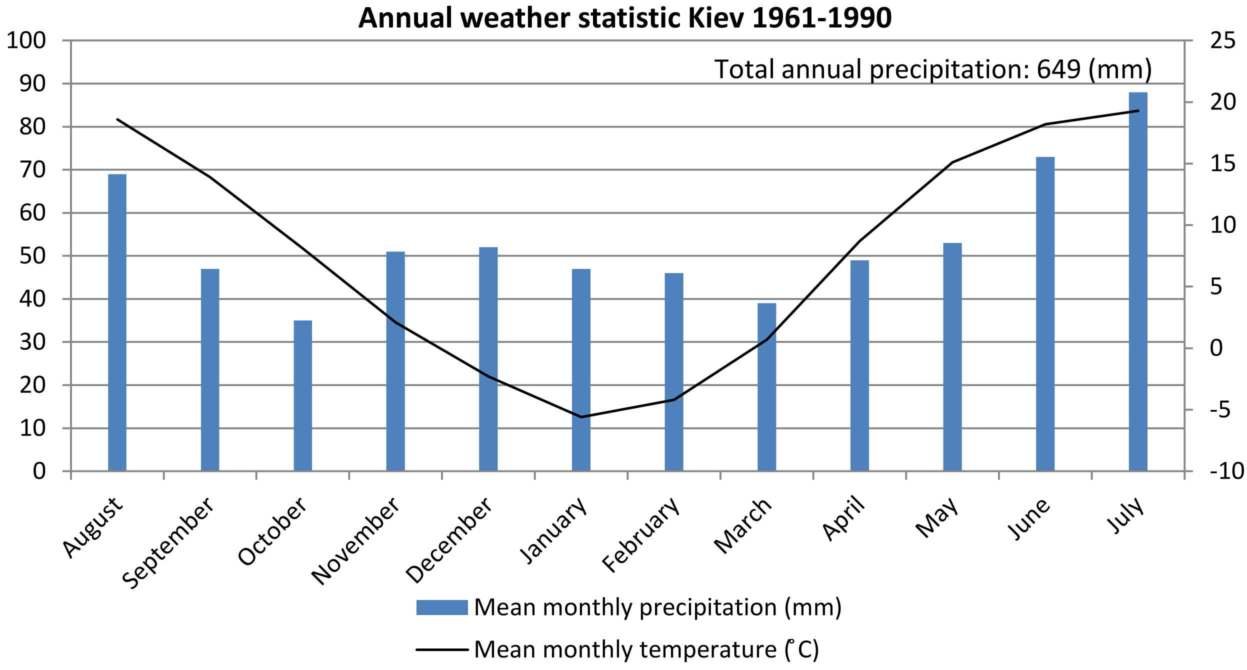


Figure 6. Long-term precipitation and temperature (monthly average 1961-1990) in the Kiev region. Data taken from WMO station 33345 in Kiev (WMO, 2015).

In the Kiev region the average temperature is below 0˚C from end of November until mid-end of February. January is commonly the coldest month, with average temperatures of -6˚C (Jones & Lister, 2009). During the winter there can be periods with severe cold that can damage the winter wheat. In the Black Sea region especially, winter kill of winter wheat is a common problem. The risk of winter kill in wheat is dependent on the temperature, the snow depth and the physiological conditions. In a frost risk simulation model, number of days with temperatures below -8˚C, -12˚C and -8˚C with 1, 3 or 10 cm snow depth can be calculated as cumulative days of damage risk. Severe winter kill in Ukraine is mainly due to a combination of little snow depth and intensive cold (Lazar, 2005). Snow cover usually takes place during the winter. The mean number of days with snow cover per year is 75-100 days in northern and western Ukraine, but declines south- and eastwards to below 50 days in the very southern parts. In the Kiev region the probability of snow cover is 70-90% in January and February and 50-70% in December and March. In November the probability of snow cover is 10-30% and in October and April it is below 10% (Bednorz, 2004). Increasing temperatures due to climate change may give milder winters, but also reduced duration of snow cover (Supit *et al.*, 2012).

The temperature increases quite rapidly during spring and reaches an average value of above 15℃ in the end of April, which compensates for a colder and later beginning of spring. This is demonstrated by the phenology of trees. Hazel flowers at the end of March in the Kiev region, which is almost a month later than in Northern Germany, Denmark and south-western Sweden. The unfolding on birch leaves, on the other hand, appears almost simultaneously in Ukraine and south-western Scandinavia (Ahas *et al.*, 2002).

In the steppe and forest steppe regions of Ukraine, the potential evapotranspiration is higher than the precipitation, which means that the growth is commonly is limited by water. The precipitation decreases from north to south and from west to east. As summer temperatures in general are highest in the parts with the lowest precipitation, the drought risk is highest in southern and eastern parts of Ukraine (Zshyvotkov, 1989). The average annual precipitation in the Kiev region is about 650 mm (WMO, 2015). There is a seasonal pattern of precipitation distribution, with the greatest amount during the summer and the least during the winter. About 65-70% is distributed during the warm season (Gusev *et al*., 1998). The highest average monthly precipitation is in July (80 mm) and lowest in December (30 mm) (WMO, 2015). Weather phenomenon can be classified in different ways according to different models. Drought is easiest classified according to annual precipitation, but potential evapotranspiration and soil water storage must also be considered for correct estimation. Potential evapotranspiration in one part of the Odessa region of southern Ukraine with comparable climate to the Kiev region is 850 mm annually. During the period April-June, when wheat has its main growth, the average evapotranspiration is 350 mm (Svitlychnyi *et al*, 2010). In simulation of weather during the 20th century, extreme droughts appear about 10 times per 100 years in the Kiev region, which is comparable to the risk for Stockholm in Sweden. There is no trend of either a drier or wetter climate in the Kiev region during the 20th century (Lloyd-Hughes & Saunders, 2002).

The day length in Ukraine and Sweden varies during the year due to latitude. Around Kiev, at latitude 50˚N, the days are longer than in Sweden (lat. 59˚N) from late September to mid-March. The difference in day length is greatest in December-January and June-July, with about 2.5 h maximum day length difference between Kiev and Uppsala (Figure 7 on next page).

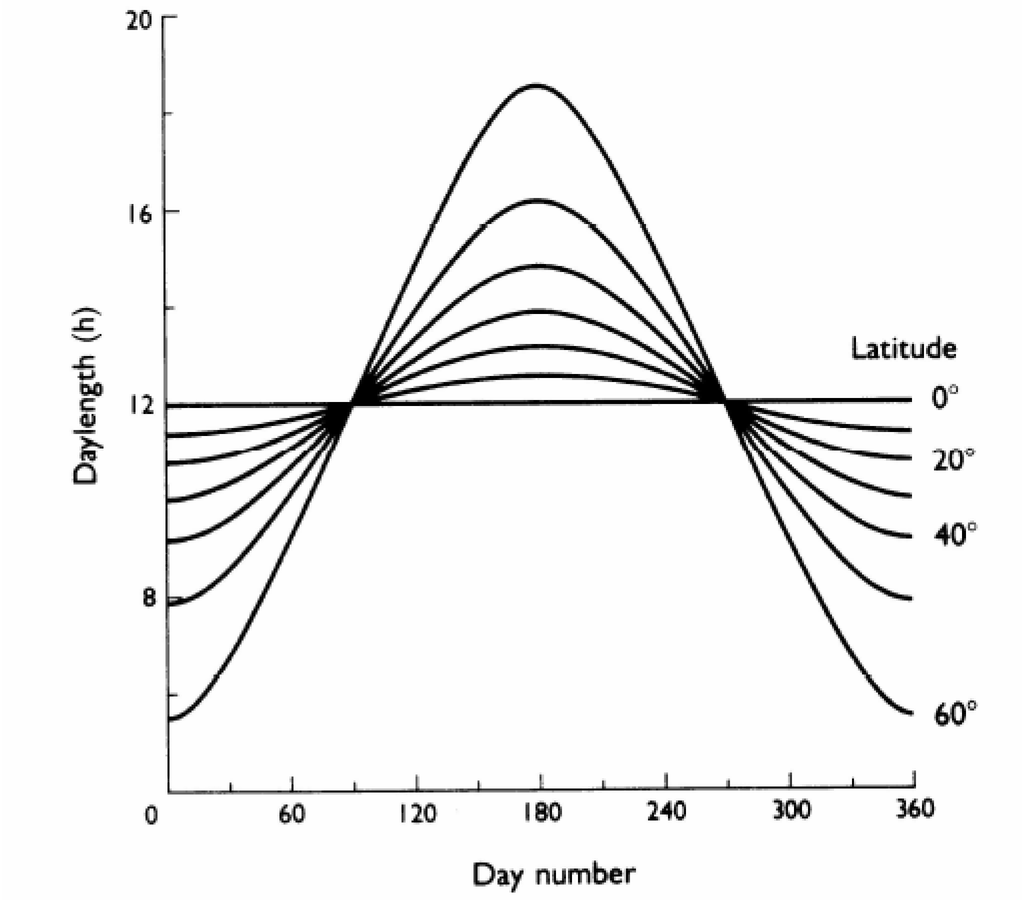


Figure 7. Day length pattern of northern Hemisphere as function of latitude. (Loomis & Connor, 1996).

The solar radiation per day, measured as kWh m^{-2} is higher in Kiev than in Uppsala all days of the years, but the difference is quite little during late spring and summer (Palz *et al.*, 1996).

2.4.2 Climate in central eastern Sweden

The weather in Uppsala region is characterized by four distinct seasons, spring, summer, autumn and winter. Figure 8 below is an illustration of a 30-year average for the period 1961-1990, with both precipitation and air temperature of the Uppsala region, see figure 8. Generally, the average temperatures during the winter months December, January and February is -3, -4 and -5℃. The spring arrives in general in the end of Mars (SMHI, 2015). During Mars and April the average temperature increase from -1 to 4℃, day temperatures is often higher but nights can still be cold. The growing season in Uppsala is in average 180-210 days (SLU, 2015). The intensity of spring growth often increase first in early May when the temperature reaches above 10℃. In summer the average temperature is between 15 and 18℃ with maximum in late July. In the autumn the temperature drops from 11 to 6℃ and 1℃ during the three months.

Over a 30-year average, it falls about 530 mm per year over the Uppsala region. The largest rainfall falls in the months of July, August and September and it comes around 60-70 mm per month. The rainfall then decreases gradually during the year. During October, November and December is falls about 40-50 mm per month and until June, does it only fall between 25-40 mm per month. Because of the low average precipitation during late winter and spring, it is not unusual with early summer drought in the Uppsala region (SMHI, 2015 (2)). The average potential evapotranspiration is 540 mm annually in Uppsala and 383 mm is during the period April-July (Wallén, 1966).

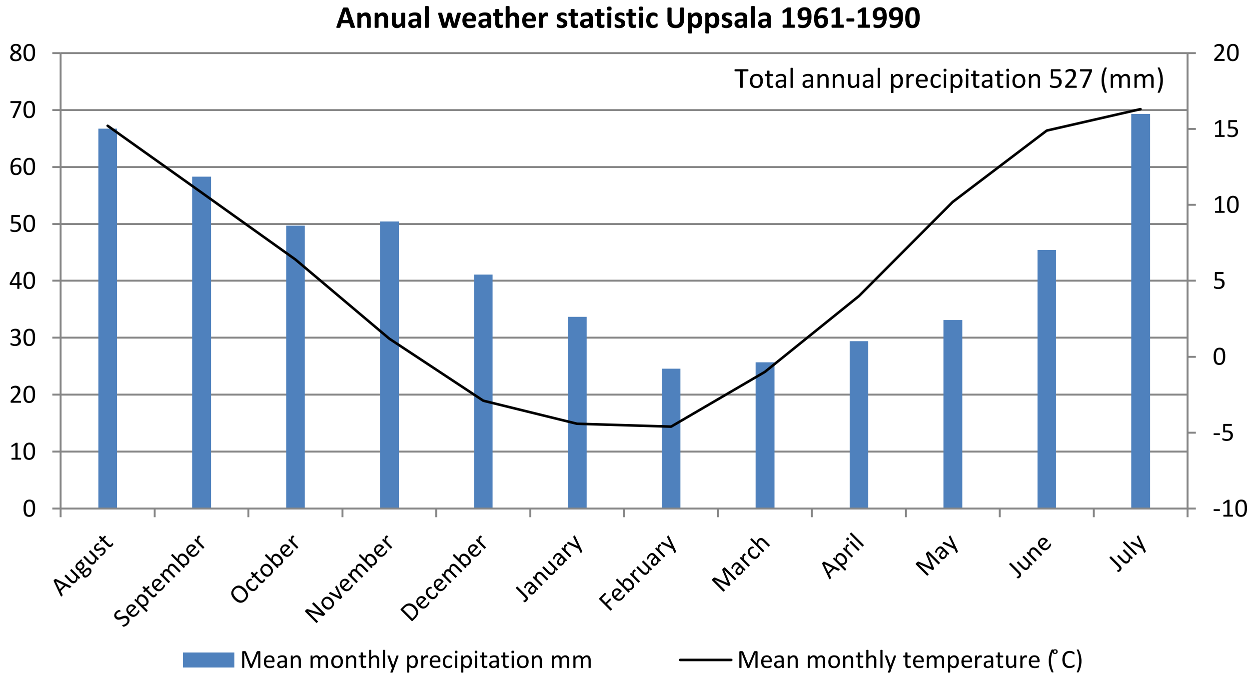


Figure 8. Illustrating precipitation and temperature on an monthly average from 1961-1990 over Uppsala region. The monthly average weather data from 1961-1990 is collected from SMHI, weather station no. 9749 at Ultuna.

2.4.3 Soils of Kiev and Ukraine

Ukraine is a large country with a very high proportion arable land. The majority of the Ukrainian soils can be classified as loess soils. These are created during long periods of deposition of dust, especially during the quaternary period that last for 2,6 million years until today. Under this period continental glaciers have covered northern Europe in successive waves and created areas without vegetation in the rim zone to the glaciers. Soil particles from these areas were transported by the wind as dust and deposited mainly on the grass plains of Eastern Europe and Russia (Vasiljević *et al*., 2014). This kind of soils is commonly referred to as loess and consists mainly of mineral particles in the size range of silt.

Loess soils are known to be very fertile due to the silt particles capacity to supply plants with water, good soil aeration and favorable root penetration properties. Loess has often adequate capacity to supply crops with mineral nutrients, rich in calcium and is easy to cultivate and get appropriate seedbed conditions. Problems with loess soils are often connected to erosion and crusting on soil surface (Catt, 2001). In parts of the world with natural or foreign steppe/prairie vegetation and climate, there has been an enrichment of humus in the soil profile. The humus content in the soil is equilibrium to the long time deposition of organic matter and the degradation rate. The organic matter of the soil has a strong impact on its properties for agriculture and therefor it is common to describe soils according to the humus content. A large part of the arable land of Ukraine is this kind of humus-rich soils, according to the USDA soil taxonomy named mollisols, but also known as chernozems, or in common words often known as black-soils/black earth. The humus content is generally highest in the surface and decrease with depth, and one parameter to define a soil as a chernozem is that the humus content at 1 m depth is above 1% (Dent *et al*., 2011). The humus in soil can have both effects on chemical properties in soil as cat ion exchange capacity, nitrogen availability, resilience against drastic changes of pH etc. But humus is also affecting physical aspects as soil structure, water holding capacity and gas exchange. Even the biological activity in the soil is generally connected to the soil organic matter (Calderón *et al*., 2001).

The soils capacity of water storage and aeration is correlated to the bulk density as high bulk density generally means low pore volume. The pore volume also affects the soils percolation capacity, root extension capability and also properties for capillary water supply (Lipiec, 2003). But these features are not only dependent on pore volume but also the structure of the pores, and very low bulk density for example in the surface of a tilled soil reduces the capillarity (Yankov, 2013). Chernozems developed on loess soil is very porous in the surface the soil, in origin grasslands with bulk densities (weight dry matter soil/volume) as low as 0,8 g cm^{-3}. If the soil gets cultivated and tillage is applied the bulk density in the upper soil will increase. Common bulk densities of cultivated heavy loam chernozems in the depth of 0-30 m depth is 1,0-1,3 g cm^{-3} with the lowest values in the upper 10 cm. In chernozem subsoils the bulk densities commonly varies between 1,1-1,4 g cm^{-3}. About 1,2-1,3 g cm^{-3} tend to be optimum bulk densities for crop growth on some different chernozems (Mamsirov *et al*., 2013). On compacted soils, roots show significant pattern of decreased growth, and concentration of roots to the top layer of soil. Compaction of soils due to heavy machineries and field actions under unfavorable moist conditions is an issue for agriculture worldwide but especially in large-scale farming on sensitive soils in humid regions. Decreased pore volume of the soil makes it more sensible for both drought and waterlogging and compaction must therefore be avoided to maintain the soil fertility. (Lipiec, 2003). Loess soils have weak structure according to the low content of clay and have therefor low capability to reconstruct soil structure if it has been damaged by compaction (Catt, 2001). The specific draft requirement, power consumption and equipment costs are considerably lower on a loam comparing to a heavy clay (Arvidsson & Magnusson, 2010). This is the case between the Ukrainian loess soil and the clay soil in Uppsala region.

In steppe regions the annual precipitation is in average lower than the potential evapotranspiration (Budyko, 1971). This means that there is a low percolation/outflow of water from the root zone of soil profile, if precipitation pattern relatively well fits to plant uptake during season. Ground water table is generally low on steppes, far below rooting depth, but depends on surrounding topography etc. During the 20th century there has been a significant increase of precipitation in the steppe regions of Ukraine and south western Russia. Temperature has increased as well but mainly in the winter and the potential evapotranspiration has not increased. The result of this is elevated ground water table levels. For example on the long-term hydrologic station in Kamennaya steppe the ground water table level has increased with about 4 m, from about 6-7 m depth to 2-3 m in an area of natural grassland during a period from 1960-1996 (Lapenis *et al*., 2008). There might be higher evapotranspiration in agricultural crops but there seem to be elevated ground water levels. According to this there is also a trend of increasing amounts of plant available water in growing season during the 20th century. In the Russian and Ukrainian grain belt the average soil moisture in winter wheat crops during June-August in 1996 was estimated to about 100 mm plant available water for a wheat crop, which was an increase with about 36 mm comparing with 1960 (Robock *et al*., 2000). Increased flows of water out of root zone increase the probability of leakage to ground water, especially calcium but also nitrate and other soluble nutrient may leach (Lapenis *et al*., 2008). At field capacity a chernozem on loess can hold about 30-35 % water of total volume in both surface, subsurface and subsoil, which is preferable for good water supply and sufficient aeration (Walczak *et al*., 2002). The porosity in a polish luvic chernozem was determined to about 47-51 % in the 20 cm of soil profile with bulk densities of 1,25-1,35 g cm^{-3}. The amount plant available water in this study was about 0,18-0,19 cm^3 per cm^3 soil and variation in the soil properties mainly according to varying tillage treatments (Glab & Kulig, 2008). Estimations of amounts plant available water in a profile must be based on several factors, as amount water at field water capacity, root depth and water content at wilting point. Chernozem on loess can hold about 20 % volumetric plant available water and have wilting point at about 15 % throughout the profile. In trials the evapotranspiration of maize increase from 1 mm water day^{-1} at water content slightly above 15 % to about 5 mm day^{-1} at 25 % water content (Novák, 2008). With an effective root depth of 1,5-2 m for a winter wheat crop the maximum amount of plant available water would be 300-400 mm. According to the fact that potential evapotranspiration is higher than precipitation in steppe climate, this kind of estimated water storage seldom exist (Webb & Rosenzweig, 1993).

Loess soils are often quite rich in nutrients such as phosphorous, potassium, magnesium, calcium etc. but varies some depending on the mother material minerals. A high saturation of cations and cation exchange capacity on loess and especially on chernozems make these soil resilience against acidification. Loess soils are as mentioned commonly known as fertile, but chernozems are especially fertile due to their great humus content. Through cultivation of these soils the equilibrium of humus in these soils are disturbed due to an increased decomposition of humus which release especially nitrogen but also other nutrients (Catt, 2001). As humus is decomposed, carbon is set free and carbon dioxide and nitrogen as mineral sources. Measurements in former USSR views significant reductions of humus stocks during the 20th century. In trials of Kharkov region Ukraine for example, the humus stock has decline with 67-79 tons ha^{-1} during 100 year (1881-1981) corresponding a reduction of humus with 21-36 % loss for measured soils, and an average annual loss of 0,7-0,8 ton ha^{-1}. With an average C:N ratio of about 10 this would mean that the about 70-80 kg N has annually been released. According to this chernozems have been able to produce adequate yields even with low fertilization rates, but with declined future fertility and huge atmospheric CO_2 emissions. The best way to stabilize humus degradation and instead increase the humus content is by reduce tillage, increase the deposition of organic matter through high biomass yield and reversal of manure and growing perennial crops (Dent *et al.* 2011).

2.4.4 Soils of Uppsala and Sweden

The soils of Sweden are very heterogeneous as the mother material has been redistributed during the last ice age that covered Sweden and deposited under different conditions. Mineral particles deposit from glaciers above sea level resulted in undivided deposit with a wide range of particle sizes, called moraines. Deposition in water led to separation of stones and coarse materials and postglacial wave washing affected the final upper layer of topsoil. The most common soil texture of Swedish agricultural topsoil is sandy loam, according to a large number of soil samples around Sweden, but there a great variations between different parts of Sweden. In the Stockholm region, north and south of the lakes Mälaren and Hjälmaren, clay and clay loams dominates (Eriksson *et al.*, 1999). It is often common with higher clay contents in the subsoil than in the topsoil. The content of clay in the topsoil in the Mälaren-Hjälmaren region is in general in the interval of 40-60 % but there local variation, mainly with lower clay content but sometimes even higher. It is common with increased clay content with depth. The amount of coarser fractions of silt often decrease with depth According to the high clay content the soils are significant aggregated and if tillage not is done in appropriate way and time, large and hard aggregates can be created in the tillaged surface (Wiklert *et al.*, 1983). Coarse structure in the seedbed may risk low seed emergence and is an advantage on clay soils (Håkansson *et al.*, 2011).

The porosity of these Swedish clay soils generally varies between 42-48 % but can be higher at very high clay content. Bulk densities of these soils often vary from 1.4-1,55 g cm^{-3}, but a compaction zone might often appear below the topsoil on 30-50 cm depth. The amounts macro-pores of total porosity is often high due to the shrinking and swelling of the clay when drought, freezing and water saturation. Clay soils have high water holding capacity which means that it can hold a high extent of water, but also that the much of the water is not plant available. Macro-pores in these soils are important for drainage and it also stimulates root growth, which is difficult in the solid clay aggregates. Potential root depths of these clays are usually about 1-1,3 m and the porosity about 45 % (Wiklert *et al*., 1983). %. At field capacity the subsoil of Swedish clays with a clay of about 50 % holds in holds about 36-47 % water, and about 26-33 % is not plant available (Andersson & Wiklert, 1972) High clay normally correlates with both high field capacity and wilting point and about 150 mm is plant available at a root depth of 1 m (Andersson & Wiklert, 1972). Clay soil has high capillary capacity but the very slow water movements make the actual capillary effect low (Wiklert *et al*., 1983). In early spring the soils in this region are commonly water saturated due to snow melting and precipitation and there is a drainage of water out of the profile (Xu, 2000). There is a hydraulic flow of water out of the soil profile in some periods of the year due to more precipitation than evapotranspiration. Swedish soils are commonly systematically drained on about 1 m depth. The ground water table is therefore connected to the drainage depth at drainage equilibrium. In periods of intensive precipitation the groundwater table may be above drainage depth and in dry periods of growing season it might be below (Wesström *et al*., 2000).

The humus content in the Mälaren-Hjälmaren region is in general 3-6 % in the topsoil, which decrease rapid with depth (Eriksson *et al*., 1999). The clays are often rich in mineral nutrients as potassium, magnesium, phosphorous and calcium. As much of the humus is incorporated in clay aggregates it is quite stable and the potential degradation rate quite low and so the nitrogen release as well (Sollins *et al*., 1996).

2.5 Crop growth models

Models to predict yields have been applied during 20th century as a tool to supply the market and policy maker with information about the annual wheat production. According to this prices and planned volumes for trade can be adjusted to match production and consumption. There are different ways to construct crop yield models and different needs of data. The less data input needed the easier model to create but often also less accurate data of yield.

Eight different yield models were compared to each other in Europe with actual yields at trial sites as reference (Palosuo *et al*., 2011). All models included following parameters: Leaf area development and light interception; Light utilization; Yield formation; Crop phenology; Root distribution over depth; Stresses involved; Water dynamics; Evapotranspiration and Soil CN-model. But the parameters were calculated in some different ways that made each model unique. The models assume there is no restriction of pests and weeds in the crop modeling. The study showed that there were surprisingly large differences between different models and between models and actual conditions of crop growth, phenology, water dynamics and yields. There were variations in the phenology modelling with as much as 20 days for anthesis between different models. Although there were in general only three parameters involved in the phenology modelling; temperature and day length, and in some models also vernalization.

Even the growth and yield performance varied a lot with both over- and underestimation. The two models that best matched the actual yield were DAISY and DSSAT with a RMSE (root mean standard error) at 1428 and 1603 kg ha^{-1} respectively.

Crop yields model can also be used to compare simulations of potential yield, based on average weather conditions with actual yield levels. In a report with the MARS-CGMS (Crop Growth Model Simulation) the water limited potential winter wheat yield in Ukraine was in average 6 tons ha^{-1}, while the actual yield in Ukraine in this period (1995) reported by FAO was 2,5 ton ha^{-1}. According to this there seem to be a great potential of yield increase. In northern Europe in for example Sweden the model estimates a lower yield level than the actual, 4,5 tons ha^{-1} comparing to actual average yield on 6 ton (Vossen & Rijks, 1995). The WOFOST crop growth model was used for comparing potential yield and yield gaps in EU-25. Under rain fed growing conditions, water limited growth model best fit to the actual yields. In these growth models yield gaps are most significant in Portugal and the Baltic states while they are lowest in Northwestern Europe. The model seems to overestimate yields in Portugal but in the Baltic States the yield gap is likely to be connected with less intensive crop cultivation. The potential water limited yield in Sweden in this model is 7-8 tons ha^{-1} (Boogaard *et al*., 2013).

During the last decades new technique and methods for crop growth measuring and simulation been available due to earth observations with remote sensing measurements and creation of Normalized Difference Vegetation Index (NDVI). For regional scale maps of remote sensing can be created from satellite measurements and can give a view of the growth conditions in the region. With narrower remote sensing observation more detailed maps can be created and field specific variations can be illustrated, for example if it is done from an airplane (Bartholomé & Belward, 2005). Growth models constructed on earth observations, meteorological data and biophysical models seems to give yield prediction as reliable as the theoretical crop growth models but with less extensive data collection to produce the simulation. Yield forecasting based on NDVI data has been done and evaluated in Ukraine during 2000-2010. In general the model overestimated the yield some comparing to official statistics, but in some case the reliability of official statistics may be disputed to. The model gave most correct estimations when NDVI measurements where done in June, prior to harvest with a RMSE of 0,3 ton ha^{-1}, when observations where done in April/May the RMSE increased to about 0,4 ton ha^{-1}. According to the model the yield levels in the Cherkassy oblast in the center of Ukraine varied between spectacular 0,7 to 4,2 ton ha^{-1} during the studied period (Kogan *et al*., 2013).

3 Method

Several of the objectives of this study required field trials to be conducted in Grain Alliance winter wheat cultivations.

Trials were set up to try to find answers on the questions mentioned below:

- Does the sowing date have any effect on the overwintering ability for winter wheat?
- How does the sowing date affect plant stand development and yield potential under given growing conditions?
- Does additional nitrogen fertilization affect plant stand development and grain yield according to the Grain Alliance fertilization strategy?
- How do different yield components contribute to final grain yield?

The study was performed in five different fields, but seven different sites cultivated in Berezan in Kiev region of Ukraine by the company Grain Alliance, Coordinates: 50.321513, 31.631673). One reference field outside Uppsala was also studied (59.810215, 17.649833), see figure 9 and 10. A phenology model was used to simulate the effect of climate on plant development.

Figure 9. Study site in Ultuna outside Uppsala, Sweden. Source: Illustration by conceptdraw.com, licensed under CC BY-NC-ND 3.0.

Figure 10. Trial and study site in Berezan east of Kiev, Ukraine. Source: conceptdraw.com Source: Illustration by conceptdraw.com, licensed under CC BY-NC-ND 3.0.

3.1 Sowing date

3.1.1 Fields, cultivations management and cultivars

Five fields with seven different sowing dates were studied in Ukraine during the growing season from September 2013 to July 2014. All the fields in Ukraine were managed by the large scale farming company Grain Alliance. The fields were situated in a radius of approximately 3 km, near the village of Berezan, approximately 60 km east of Kiev. The soil type was assessed to be similar in the different fields. Grain Alliance soil surveys for the different fields also showed a quite homogenous pattern with pH-values of 6-6,5. All the fields in the study had sunflower as preceding crop. Before sowing the fields were fertilized and crop residues were incorporated by a chisel plough. The tillage depth was 10-12 cm and the incorporation of crop residues was quite good even if the sunflower stalks were hard to decompose. The ground surface after tillage was quite uneven and sometimes a harrow was used as a complement for seedbed preparation. The studied winter wheat in Sweden was grown on a clay soil. The preceding crop was pea and a cultivator was used for primary tillage and a harrow for seedbed preparation.

The winter wheat in the studied fields in Berezan were seeded in a period from mid-September to early October, see table 1. These sowing dates can be aggregated to three groups, mid-early in field 1.1 and 1.2, sown in 13th -18th September, mid-late, field 2 sown in 26th of September and late for field 3, 4, 6.1 and 6.2 sown in 3rd -7th October. The same variety of winter wheat was used in field 1.1, 1.2 and 2 but three other different varieties were used in the other fields. The amount of seed used was according to Grain Alliance´s strategy of seed rates, correlated to sowing date and cultivar. As sowing only could be conducted during periods of favourable conditions sowing dates do not correspond to a continuous interval. Field 3, 4, 6.1 and 6.2 is sown in an interval of four days and can be seen as repetitions of a late sowing date.

At Ultuna the sowing date was 7th September and the seed rate was 450 germinable kernels m^{-2}.

Table 1. Varieties, sowing date, seed rate and germinability for the different fields in the study. Data collected from Grain Alliance and the Department of Soil and Environment at the Swedish University of Agricultural Sciences

Field		Variety	Sowing date	Seed rate (kg ha^{-1})	Moisture, %	Tkw	Germination, %	Germinable kernels m^{-2}
Field 1	Bilya gnoyarki	*Polishka-90*	(13/9)	310	12,2	49,7	97	607
Field 1.2	Bilya gnoyarki	*Polishka-90*	(18/9)	310	12,2	49,7	97	607
Field 2	Malosupoivske	*Polishka-90*	(26/9)	310	12,2	49,7	97	607
Field 3	Bilya alei	*Analog*	(3/10)	370	12,3	51,9	97	692
Field 4	Samuseve	*Sonechko*	(7/10)	360	12,3	46,9	97	745
Field 6.1	Bilya skoryka	*Skagen*	(5/10)	360	12,7	43,5	97	802
Field 6.2	Bilya skoryka	*Sonechko*	(6/10)	360	12,3	46,9	97	745
Field 7	Ultuna	*Olivin*	(7/9)	214	13,5	45,6	96	450

All the studied fields and trial plots in Ukraine was chemically treated on the basis of the company's normal winter wheat strategy. The chemical treatments with herbicides, fungicides and insecticides that were applied in Ukraine and Ultuna are presented in table 2.

Table 2. Dates of chemical treatments in Berezan and Ultuna 2013-2014

Field	Herbicide		Herbicide	Fungicide		Growth regulator	Insecticide
	Grodyl Maxi (0,1 L ha^{-1})	Prima (0,6 L ha^{-1})	CDQ SX (25 g) S Starane 180 (0,5Lha^{-1}) Hormotex (1L ha^{-1})	Rex Duo (0,5 L ha^{-1})	Falcon (0,6 L ha^{-1})	Chlormequat chloride 750 (1,9 L ha^{-1})	
1.1	17-19 April	(-)	(-)	16-23 May	16-23 May	28 April - 3 May	(-)
1.2	- II -	(-)	(-)	- II -	- II -	- II -	(-)
2	(-)	22-26 April	(-)	- II -	- II -	- II -	(-)
3	- II -	- II -	(-)	- II -	- II -	- II -	(-)
4	- II -	(-)	(-)	- II -	- II -	- II -	(-)
6.1	- II -	(-)	(-)	- II -	- II -	- II -	(-)
6.2	- II -	(-)	(-)	- II -	- II -	- II -	(-)
Ultuna	(-)	(-)	15 April	(-)	(-)	(-)	(-)

- II - (As previously date), (-) (None treatment performed).

In the trials in Ukraine four different varieties were grown. Three of them were bred in Ukraine (Polishka-90, Analog, Sonechko) and the last one was bred in Denmark (Skagen). At the field in Sweden, a German bred variety was grown (Olivin).

Skagen

Skagen is a Danish-bred bread wheat with moderate yield level but good overwintering ability Medium to early maturing (315 days in Sweden), relatively tall variety (84 cm) and with relatively weak straw. Skagen has relatively small ears with on average 39 kernels per ear, but high thousand kernels weight (49 g) compared to other cultivars in the Swedish list of varieties (Hagman *et al*., 2014; Official trials 2009-2013, www.slu.se/faltforsok).

Olivin

Olivin is a German bred bread wheat with moderate yield level and very good overwintering ability. It is medium to early maturing (316 days in Sweden), quite tall (86 cm) and has relatively good straw strength. The number of kernels per ear is high, 46 kernels per ear, but the thousand kernel weight is relatively low (45,1 g) (Hagman *et al*. 2014; Officiella försök 2009-2013, www.slu.se/faltforsok).

Polishka-90

Polishka-90 is a Ukraine bred winter wheat variety, originated from NSC (National Scientific Centre). It is recommended for cultivation in the forest-steppe zones of Ukraine and Polisskiy. Recommended seed rate is 400-500 seeds m^{-2} and recommended sowing dates in Polissya is 10-15 September and forest steppe 15-20 September. Plant height 105–110 cm. Medium-early maturity, with good frost and winter hardiness.

Analog

Analog is a Ukraine bred winter wheat variety, originated from NSC "Institute of NAAS". Analog was registered in the register of plant varieties of Ukraine in 2008. It is recommended for cultivation in the forest-steppe zones of Ukraine. Recommended seed rate is 500-550 seeds/m^2 and recommended sowing dates in forest-steppe is 15-22 September. Plant height is 67-85 cm when using growth regulator. It is a drought-tolerant variety with large kernels. The growing season is about 285-288 days in forest-steppe regions of Ukraine (SEEDS OF UKRAINE & Oranta Antaria, 2015).

Sonechko

Sonechko is a Ukraine bred winter wheat variety, originated from the institute of plant physiology and genetics, NAS (National Academy of Sciences). It is recommended for cultivation in Polisskiy, the steppe and forest-steppe zones of Ukraine. Recommended seed rate is 450-550 seeds/m^2 depending on area and sowing date. Plant height is 71-76 cm when using growth regulator and the variety is quite resistant to lodging. The growing season is about 280-287 days in Ukraine. Thousand kernel weight is normally in the interval 38-45 g (Farm "Grieg", 2015).

3.1.2 Plant observations

Effects of sowing date were studied through observation of winter wheat seedlings. In each field in Ukraine and at the reference field in Sweden an assessment of the winter wheat stand was conducted to characterize plant and stand development. The assessment started in the autumn 2013 at DC 13-22 by counting and measuring: seedlings, number of tillers, number of leaves on the main shoot, leaf length of longest leaf, dry matter weight seedlings and sowing depth. In table 3, dates for all these minor field studies are presented.

Table 3. Specific dates for field studies; no. of seedlings and shoots, leaf on head shoot, harvest and profile excavation with addition connected studies (moisture tests etc.) were performed

Field	Seedling and shoot number		Leafs on head shoot, Longest leaf, Sowing depth	Visual observation in DC 75-77 (Crop lodging, pest observation etc.)
	Autumn	Spring		
1.1	19-20 Nov	13-15 April	19-20 Nov	17 June
1.2	- II -	- II -	- II -	- II -
2	- II -	- II -	- II -	- II -
3	- II -	- II -	- II -	- II -
4	- II -	- II -	- II -	- II -
6.1	- II -	- II -	- II -	- II -
6.2	- II -	- II -	- II -	- II -
Ultuna	15 Nov	9 April	15 Nov	(-)

In spring observations were conducted again with count of seedlings and number of tillers at DC 21-23. The seedling counting was made within steel frames of 0,25 m^2 in Sweden and a steel frame of 0,285 m^2 in Ukraine, which was repeated six times for each seedling counting, see figure 11. The method of plant counting had to be changed as it was difficult to distinguish individual seedlings within the steel frame in the spring due to high plant density and a significant tillering in the spring. The seedlings within the frame had to be dug up and counted, which was much more time consuming and therefor only one square of 0,285 m^2 was counted at each site in the spring instead of six in the autumn, see figure 12. In the autumn, 20 random seedlings were sampled from each trial site. These seedlings were used to determine leaf length, number of tillers, sowing depth and DM weight. The sowing depth was estimated by measuring the color change from white to green on the straw base to the kernel. To calculate the weight of the dry matter of the seedlings, they were dried in 105 ^{0}C for two days.

In 17th of June ocular observation of the winter wheat plant stands in DC 75-77 were done in Ukraine. Crop lodging, possible pest damage, plant height and ocular stand density were noticed.

Figure 11. To the left: seedlings with different numbers of tillers in Berezan, Ukraine. To the right: counting with steel frames in Berezan, Ukraine. Source: Mats Magnusson and Jakob Eriksson.

Figure 12. To the left: dense winter wheat stand (13/4) in Berezan, Ukraine. To the right: seedlings of a steel frame area is dug up and counted in Berezan, Ukraine. Source: Mats Magnusson and Jakob Eriksson.

3.2 Fertilization

Fertilization experiments were conducted in the same fields where plant observations of wheat with different sowing dates were performed. Trials were setup to compare different rates of nitrogen and application time.

3.2.1 Trial setup

The fertilization trials were performed with six different treatments. The minimum level of nitrogen was application in form of granulated mono ammonium phosphate (MAP) at the time of sowing, broadcast granulated ammonium nitrate (AN) in mid-April and foliar applied urea in May. All these actions were performed by Grain Alliance according to their winter wheat management strategy. Differences between treatments were based on varying rates of liquid urea ammonium nitrate (UAN) and time of application, see table 4.

Table 4. Different fertilization levels in trials

Type of application	Product (Kg N ha^{-1})	Date	Treatment A	B	C	D	E	F
Band	MAP	11 sep-6 Oct.	6	6	6	6	6	6
Broadcast and incorporate	UAN	11 sep-6 Oct.	0	0	0	48	48	48
Broadcast	UAN	8-15 Mars	0	0	0	64	64	0
Suspended in water and broadcast*	UAN	17 April	0	64	112	0	40	64
Broadcast	AN	17-21 April	32	32	32	32	32	32
Foliar application	Urea	28 apr-2 May	5	5	5	5	5	5
Foliar application	Urea	17-22 May	5	5	5	5	5	5
Total kg N ha^{-1}			48	112	160	160	200	160

*Manually applied fertilizer in trials

Treatment B was fertilized according to Grain Alliance general management practice of winter wheat in Berezan 2014. A, B and C were not fertilized with UAN in autumn but three different rates of UAN in spring, 0,64 and 112 kg N ha^{-1}. Treatment E was similar to treatment D but with additional 40 kg N ha^{-1}. Treatment F is set up to show possible effects of delayed nitrogen application in spring as reference to treatment D. Important to note is that field 2 has been fertilized with 32 kg N less than other fields.

In the Swedish field only one fertilization level was studied. Nitrogen was applied as granulated ammonium nitrate 15th April at a rate of 140 kg N ha^{-1}.

Fall fertilization was performed in field no. 1.1, 1.2, and 2 before trial design of the fertilizer experiment was set. According to this it was decided to just compare the normal nitrogen fertilization rate and normal with additional 40 kg N, treatment D and E, in these fields, see table 5.

Table 5. Fertilization treatments in different fields

	Treatments (Kg N ha^{-1})					
	A	B	C	D	E	F
Fields	48	112	160	160	200	160
1	(-)	(-)	(-)	D	F	(-)
1.2	(-)	(-)	(-)	D	F	(-)
2	(-)	(-)	(-)	D	F	(-)
3	A	B	C	D	E	F
4	A	B	C	D	E	F
6.1	A	B	C	D	E	F
6.2	A	B	C	D	E	F

The fertilization of nitrogen in the trial was done by hand, the 17th April 2014. The trail plots for the different fertilization levels were also marked by yellow markers on the 17th April, see figure 6. In field 3, 4 and 6 full-scale trials were established. Each trial plot was 4 m^2 in a square with 6 different treatments and two repetitions per field. As the fertilization trials had to be conducted in separate parts of field 6 sown with different varieties, this field was handled as two fields (6.1 and 6.2) with only a single repetition instead of one field with two repetitions. This led to that treatment B, C and F in field 6.1 do not have any repetition nor treatment A, B, C, D, E and F in field 6.2. In field 1.1, 1.2 and 2 only two treatments with two repetitions were conducted. To make the plots more visible later on the season, the plots were meant to be marked with agriculture fiberglass stakes at the same time. Unfortunately fiberglass stakes were not available in Berezan and wooden sticks had to work as substitute, see figure 6.

Four out of the six treatments included manual fertilization in the spring with the fertilizer UAN 32 according to table 5. This nitrogen source is commonly used by Grain Alliance in their wheat cultivation, and also considered to be both easier and more secure to apply, than nitrogen as granulate. In order to facilitate the application further the UAN was diluted with water, and the mixture was applied evenly over the plot-boxes with a water can, see figure 13. The amount of water that UAN was diluted with was equivalent 2 mm of rainfall.

Figure 13. To the upper left: Fertilization by hand in the fertilization trial on the 17th April, Berezan. To the upper right: Yellow markers, marking four plots in the fertilization trial on the 17th April, Berezan. To the lower left: Wooden sticks which had to work as substitute for normal fiberglass stakes. To the lower right: Wooden sticks that mark the fertilization plots. Source: Mats Magnusson and Jakob Eriksson.

3.2.2 Plant observation and harvest practice

17th June the plant stands (in DC 75-77) were investigated regarding plant health, weed competition, plant height and lodging frequency, see figure 14. The fertilization trials were observed according to colour and density as reference to different fertilization levels.

The principle of harvest was to measure grain yield as well as the three yield building components; numbers of ears per m^2, number of kernels per ear and grain weight (thousand kernel weight, tkw). According to this the harvest of the trial plots were done by hand with scissors. From each fertilization trial plot (2m*2m), four individual samples were collected by harvesting four squares of (50*57 cm) with help of steel frames. The steel frames were placed as centrally as possible in the plots to avoid edge effects. The ears from each of the square (0,285 m^2) were collected and put into bags.

Figure 14. To the left: Visual assessment of an winter wheat stand at DC 75-77 in Berezan, Ukraine. To the right: Harvest of the fertilization trail in Berezan, Ukraine. Source: Mats Magnusson and Jakob Eriksson.

All bags with ears from each plot ware weighed, but the number of ears was counted in the bag with a weight closest to the average weight of the four samples. A smaller sample of these ears were put into smaller paper bags and dried in 105 ˚C for about two days. Weights were recorded and 20 ears were randomly collected and processed by hand so grains and ear residue were separated and the grain weight was noted. The ratio between grain weight and ear weight was measured for each sample. The thousand grain weight was determined by counting 200 kernels that were weighed. All samples were dried for five days back in Sweden, until no further weight loss could be noted and the humidity was assumed to be 0 %. The grain yield and yield parameters was calculated from the measured values and adjusted to represent storable grain with 14 % water content. Unfortunately no nitrogen content (protein) measurements were carried out on any grain from the trials. In the Swedish field, grain yield and thousand kernel weight were harvested and measured by the department of Soil and Environment at the Swedish University of Agricultural Sciences.

3.3 Profile excavation, root development and soil water availability

Three pits were dug for this study, in order to get more accurate data on soil condition and soil properties at the different trial sites. Two profile excavations were done in Berezan and one at Ultuna and aggregate size, root depth, bulk density and soil water were measured. The profile was described and soil type measured and earthworm presence determined.

Figure 15. Profile pit, covered in plastic in Berezan, Ukraine. Source: Mats Magnusson and Jakob Eriksson.

The two pits in Ukraine were dug in 2014-04-12 and the one in Sweden was dug in 2014-05-15 to a depth of 150-160 cm. The pit in field 1.1 was dug quite close to the field border, which is more trafficked by heavy machinery than the rest of the field. The pits were covered with plastic so a second measurement of soil water content could be done later in the season, see figure 15.

The root depth was determined by observing the maximum depth at which vital roots were found. Aggregate structure and aggregate size were determined by ocular assessment.

From fields 1.1 and 3, two soil samples for were collected for texture analysis (pipette method), one in the topsoil (10-15 cm depth) and one from the subsoil (40-45 cm depth). Earthworm presence was determined by digging up a volume of 20*20*10 cm soil and determining the number of worms in the defined volume. The bulk density was measured by taking out three steel cylinders (72*50 mm) at 10-15 cm and 40-45 cm depth which then were weighed both before and after the samples were dried in 105 ˚C for two days, see figure 16 on next page.

Figure 16. To the left: three steel cylinders at 40-45 cm depth in a winter wheat field in Berezan, Ukraine. To the right: bulk density samples weighed and later dried at the soil laboratory in Yagotin, Ukraine. Source: Mats Magnusson and Jakob Eriksson.

Figure 17. To the left: soil samples becoming dried at the soil laboratory in Yagotin, Ukraine. To the right: moisture meter in winter wheat field at Ultuna, Sweden. Source: Mats Magnusson and Jakob Eriksson.

On two occasions, the water content in the soil was measured to a depth of 150 cm. The first measurement was conducted when the pits were dug (12th April in Ukraine and 15th May in Sweden) and the second measurement was done 18th June in Ukraine and 5th June in Sweden. The water content was determined by two methods. Gravimetric soil water content was determined on soil samples from different depths that were weighed and dried in 105 ˚C for two days. The volumetric water content was determined with Delta T soil moisture equipment, see figure 17. The volumetric amount of water in the soil profile was also calculated from the gravimetric water content and the bulk density of the soil, according to the equation:

$$Volume\ water\ \% \ = {}^{mw}/_{ms} * \ \partial d * 100$$

Where: m_w = weight water, m_s = weight soil, ∂d = dry bulk density of soil

The density of water is set 1,0 g cm^{-3}. After comparison with literature values, the values from 40-45 cm depth was used for the calculation of the water volume percentage for the whole profile depth. Bulk densities and permanent wilting points for calculation of plant available water at Ultuna was collected from literature on an equal soil nearby Ultuna. For the Ukrainian soil the permanent wilting was measured in the laboratory.

3.4 Phenology model

Phenology models for winter wheat predicts the time (date) of different development stages and the abiotic parameters involved the modelling is normally temperature and day length, but in case of winter wheat often also vernalization is included. In the model used in this thesis, vernalization is just assumed to be fulfilled the first of January. The developmental thresholds values in form of degree-days for different development stages are collected from a phenology model created by Henrik Eckersten (2003). The different development stages involved in the model with respective value of degree-days are: floral initiation (15), double ridge (151), terminal spikelet (85), ear appearance (204), end of anthesis (193), grain fill start (31), grain fill stop (256) and maturity (63). The degree-days presented are a summary of photoperiod adjusted degree-days above the base temperature 1℃ from floral initiation to the end of anthesis, and above 9℃ from anthesis until maturity. The original phenology model created by Eckersten (2003), was calibrated after winter wheat grown at Ultuna during 2002-2003. One important difference between the calibrated year and the simulated, is that the date of vernalization was fulfilled 18/1 at the calibrated year. For the model to give the most accurate simulations the winter wheat cultivation scenarios should be carried out in the same area and with the same variety of winter wheat as it was calibrated for, in this study Ukraine. Unfortunately to few development stages were noticed during the growth season 2014 to calibrate the model after the winter wheat cultivars studied in this thesis.

The difference between Ukraine and Sweden are not only the temperature, but also the latitude that affects the day length as this is also an important development factor until flowering. In the model a photo-value is calculated, which decides how much of the temperature which is over the base temperature that should be counted and accumulated. A day length of 20 hours is needed for the maximum value of 1.0. The accumulation of degree-days starts at the first of January in this model, this is because the vernalization is not included. In early January the day length in Uppsala barely reaches six hours (photo-value 0,29) and in Ukraine, eight hours (photo-value 0,40). In June in Uppsala it reaches its maximum, which is about 18 hours (photo-value 0,9) and Ukraine reaches just over 16 hours (photo-value 0,8). In this model two different base temperatures are used. The base temperature decides at which temperature the model starts to accumulate degree-days. After flowering wheat development is not sensitive to photoperiod but just to temperature.

In this study, the model was used to simulate developmental stages for winter wheat growing in the seasons 2013-2014, 2012-2013 and 2011-2012 in Berezan, Ukraine and 2013-2014 in Ultuna, Sweden. The main purpose with the simulations was to be able to see differences in occurrence of development stages between wheat grown in Ukraine and Sweden and hopefully increase our understanding of the individual yield potential at the two locations.

Climate data 2009-2014 for the trial area in Berezan, Ukraine was taken from a weather station from World Meteorological Organization with station no. 33356 located in Yagotion, which is about 10-15 km east of the area where the trials were conducted. Due to the geographical distance to the weather station, the values of the trial site may differ slightly from the weather station values. The weather data for 1961-1990 average over Kiev is collected from WMO station no. 33345 located in Kiev. The average weather data over Uppsala 1961-1990 is collected from Swedish Meteorological and Hydrological Institute (SMHI). The climate data for growing season 2013-2014 and 2002-2003 are collected from Lantmet at Swedish University of Agricultural Sciences (SLU) / Fältforsk and Swedish Meteorological and Hydrological Institute (SMHI).

3.5 Calculations and statistics

The collected data from the trials was originally written into Excel and then transferred over to SAS (Statistical Analysis Systems Institute, Incorporated, Cary, USA, version 9.2) for the analysis of variance (ANOVA). The threshold for significance was set at 5%-level ($p = 0,05$). Of the collected data from Ukraine, analysis of variance was tested on seedling characteristics (autumn and spring), yield levels and yield components.

3.6 Literature study

The extent of the literature study is substantial in this thesis. The hope was that an extensive literature study could provide some answers to the issues raised in this paper. Unfortunately, very few reports published from Ukraine could be found. The problem is probably not that there are no publications, the problem is rather that they are not written in English. This resulted in that much literature was based on peer reviewed articles from other countries. Quite a lot of the referred articles are from USA which was assessed to have some parts that have a similar climate and cultivation strategy as Grain Alliance has in Ukraine.

4 Results

4.1 Weather statistics

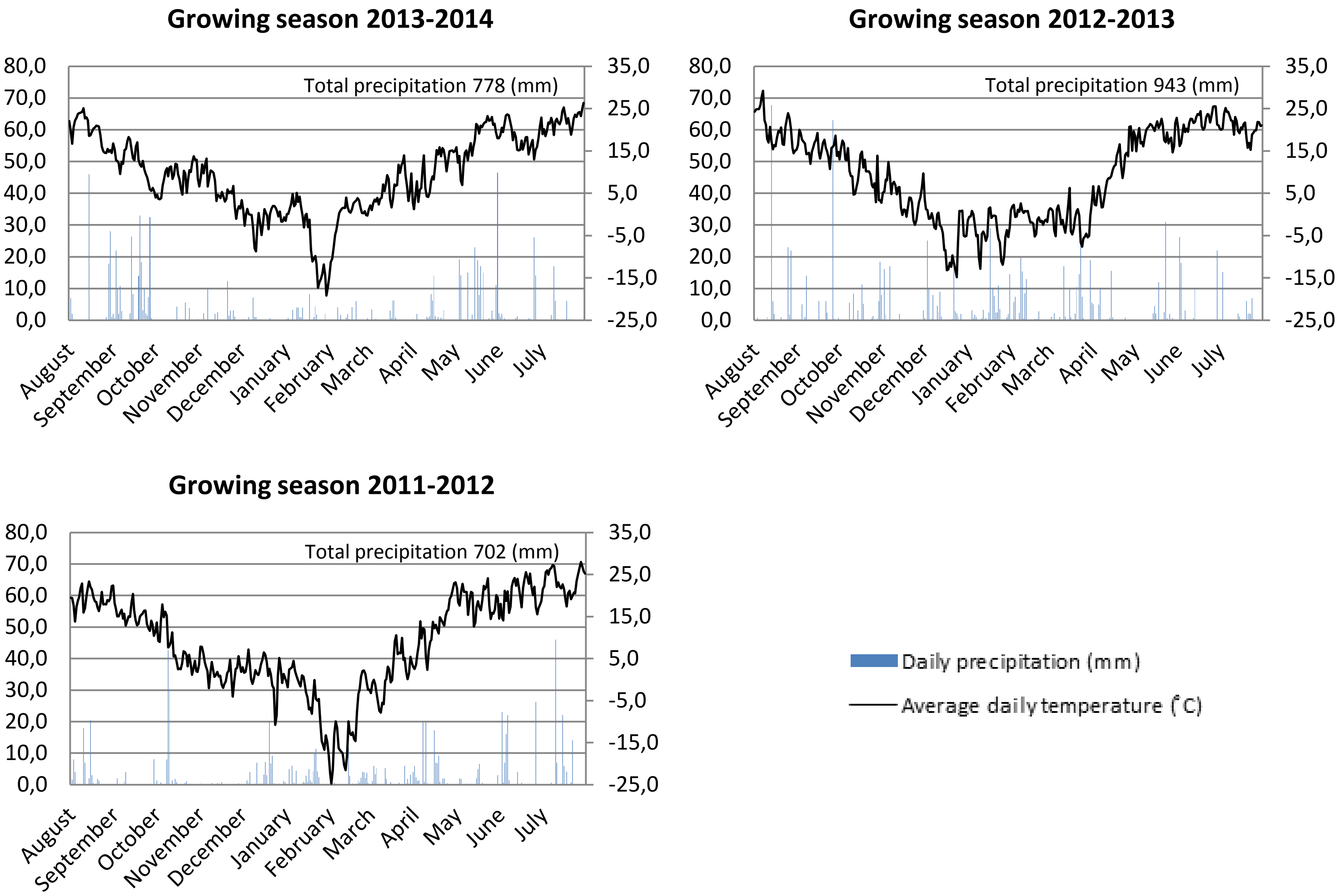
4.1.1 Weather description of the individual year

The years are described according to the growing season for winter wheat with beginning in the autumn and end in the next summer.

The growing season of 2013-2014 (August-July) in Berezan was characterized by a very heavy precipitation in September, relatively mild and dry winter and with a very wet May, see figure 18. The total precipitation was about 780 mm which is 130 mm over the 30-year average. The autumn was on average wetter and milder than the average year and the winter was milder and drier. The spring was early and initially drier than average but was compensated greatly by the 194 mm that fell in May. The temperature during June and early July was normal and the precipitation was slightly below average.

The growing season of 2012-2013 in Berezan was characterized by large amounts of precipitation in winter and spring and with high temperatures during the summer months, see figure 18. The total precipitation was about 300 mm over the 30-year average. The autumn was on average wetter and milder than the average year. The winter months and months until April were also wet. Overall there was nearly 600 mm of precipitation between September and April. The spring was slightly late due to low temperatures in the March. The months of May, June and July was warmer than average.

The growing season of 2011-2012 in Berezan began with a normal autumn regarding temperature and precipitation. The winter was long and cold, with especially low temperatures during February when the average temperature was -11℃. The rapid rise in average temperature from a cold March to a warm April (-1℃ to 13℃) resulted in a short and intensive spring. The last months of May, June and July was much warmer and slightly wetter than average. The total precipitation was about 50 mm over the 30-year average, see figure 18 on next page.


Growing season 2013-2014

Growing season 2012-2013

Growing season 2011-2012

Figure 18. Precipitation and air temperature on daily mean values from the three latest growing seasons in Berezan, 2014, 2013, 2012. The daily men values is collected from WMO station no. 33356 located in Yagotin.

The growing season of 2013-2014 in Uppsala began with a slightly dry weather in early autumn, otherwise normal temperature and precipitation. The winter was milder and wetter than average. The same applied to spring that was both early and wetter than average and the rainfall during the spring and early summer were sufficient to prevent a possible early summer drought. The month of July was very dry and warm. The total rainfall was in line with the average year, see figure 19.

The growing season of 2002-2003 in Uppsala began with dry and warm weather in August, otherwise the temperature and precipitation were normal throughout the autumn, until the month of December. It was on average a cold winter with low precipitation from December to March. April, May and June were wetter than the average. The month of July was very dry and warm. The total rainfall was about 130 mm below the average year, see figure 19 on next page.

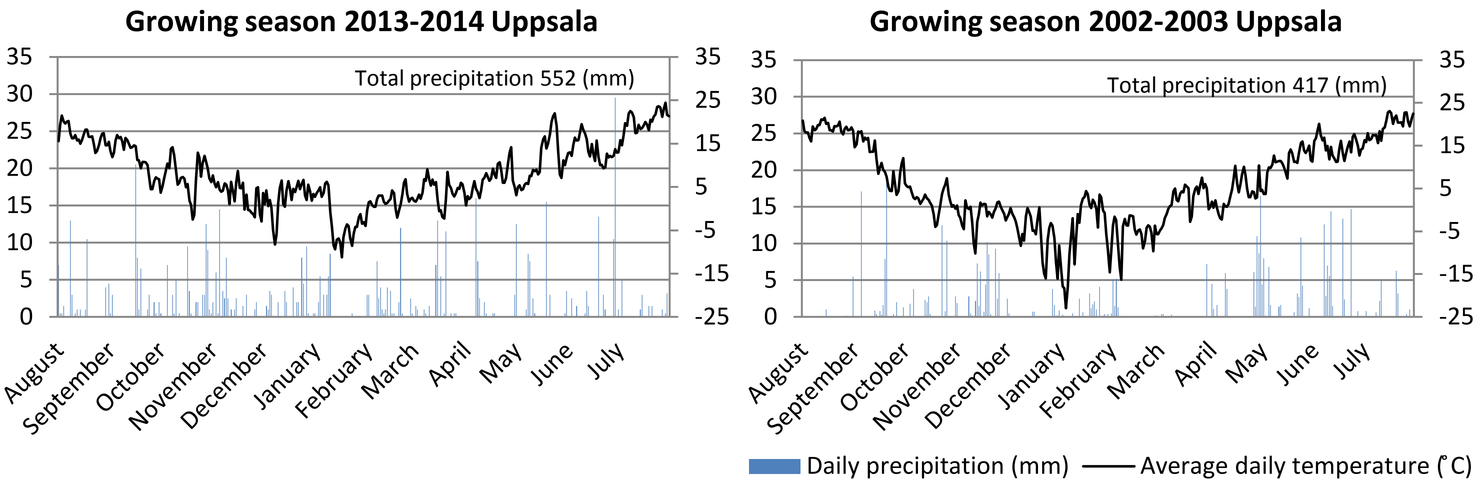


Figure 19. Precipitation and temperature for growing season 2013-2014 and 2002-2003 at Ultuna/Uppsala. The average daily air temperature is collected from Lantmet at SLU / Fältforsk weather station Ultuna and the daily precipitation is collected from SMHI weather station Uppsala.

4.2 Sowing date

4.2.1 Plant observations

Summarized data from the plant countings are presented in table 6. Variance analysis was done on the fields 1-4. Field 6.1 and 6.2 are excluded because of limited amount of data. However, there are data from field 6.1 and 6.2 in the same table, but they are not included in the variance analysis.

Table 6. Mean values from the seedlings counting. Variance analysis are made on the values with sufficient amount of repetitions. Values that are not followed by the same letter are significantly different (p<0.05)

		Fields						
		1.1	1.2	2	3	4	6.1*	6.2*
Sowing date		(13/9)	(18/9)	(26/9)	(3/10)	(7/10)	(5/10)	(6/10)
Sowing rate (g.k./m^2)		607	607	607	692	745	802	745
Seedling emerging		67%	70%	69%	62%	80%	63%	68%
Seedlings/m2	Autumn	404 (b)	424 (b)	420 (b)	431 (b)	598 (a)	505	506
	Spring	365 (b)	380 (b)	547 (a)	581 (a)	592 (a)	554	546
Shoots/m2	Autumn	1275 (a)	1045 (ab)	774 (c)	452 (d)	896 (bc)	656	726
	Spring	1310 (ab)	1256 (ab)	1713 (a)	1190 (b)	1596 (ab)	1414	1613
Biomass/seedling (g)	Autumn	0,17 (a)	0,11 (b)	0,08 (bc)	0,04 (cd)	0,04 (d)	0,04	0,03
Tillers /seedling	Autumn	2,17 (a)	1,47 (b)	0,87 (bc)	0,05 (d)	0,52 (cd)	0,3	0,43
	Spring	2,62 (a)	2,3 (ab)	2,17 (ab)	1,08 (b)	1,8 (ab)	1,55	1,95

* Fields with a limited amount of data from the plant counting.

Plant number was in general higher in late sown wheat but the plant stands were a lot denser in early sown wheat due to an extensive tillering, see figure 20.

Figure 20. Photos of two wheat stands 21th November. Left picturfield 4 with Sonecko, sowing date 7/10, sowing rate 745 g. k./m^2 and right picture field 1.1 with Polishka-90, sowing date 13/9, sowing rate 607 g. k./m^2.

The tillering frequency as a function of sowing date is also presented in figure 21 below.

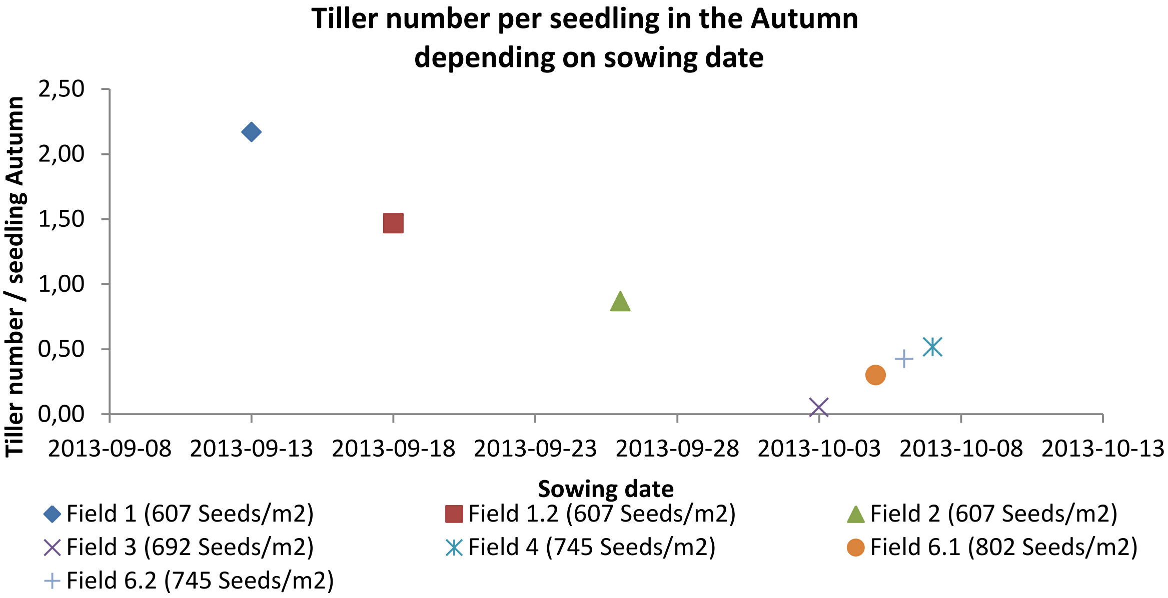


Figure 21. Tillering frequency as a function of sowing date, sampling date 21th November.

Field 1.1 differs significantly from other fields by a higher biomass per plant. A significant trend between sowing date and plant weight is illustrated in figure 22. An earlier sowing date resulted in a larger biomass.

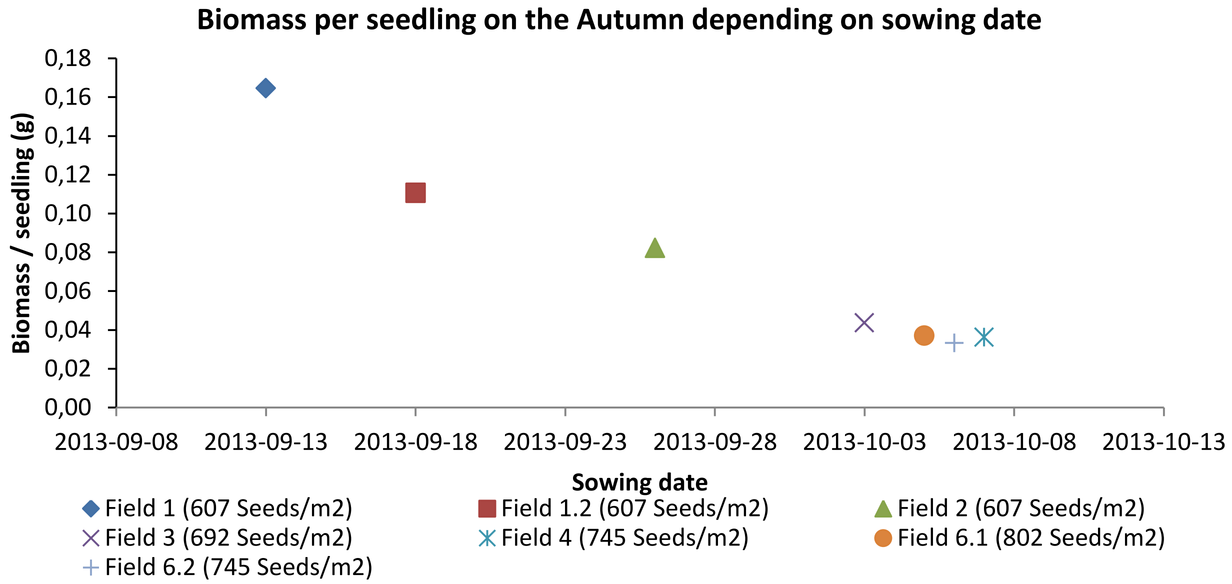


Figure 22. Dry matter weight for seedling of wheat, measured 21th November as a function of sowing date,.

The ocular evaluation indicated no plant death during overwintering of the wheat, neither in general thinning of plant stand, nor of specific damaged sites. The average number of plants increased according to the data, see table 6, but it should be noted that different methods for investigation of plant number was used in the fall and in the autumn.

The variation in the number of shoots was somewhat levelled out in the spring compared to the autumn due to tillering in spring. This was most significant in the late seeded fields. Still the number of tillers was highest in the earliest seeded fields, see figure 23. Only in field 2 and 3 there was a significant difference in total number of shoots. The reason to the difference seems to be the low tillering in field 3 in both autumn and spring. Fields with a substantial tillering level in the autumn had in general a lower extent of tillering in spring.

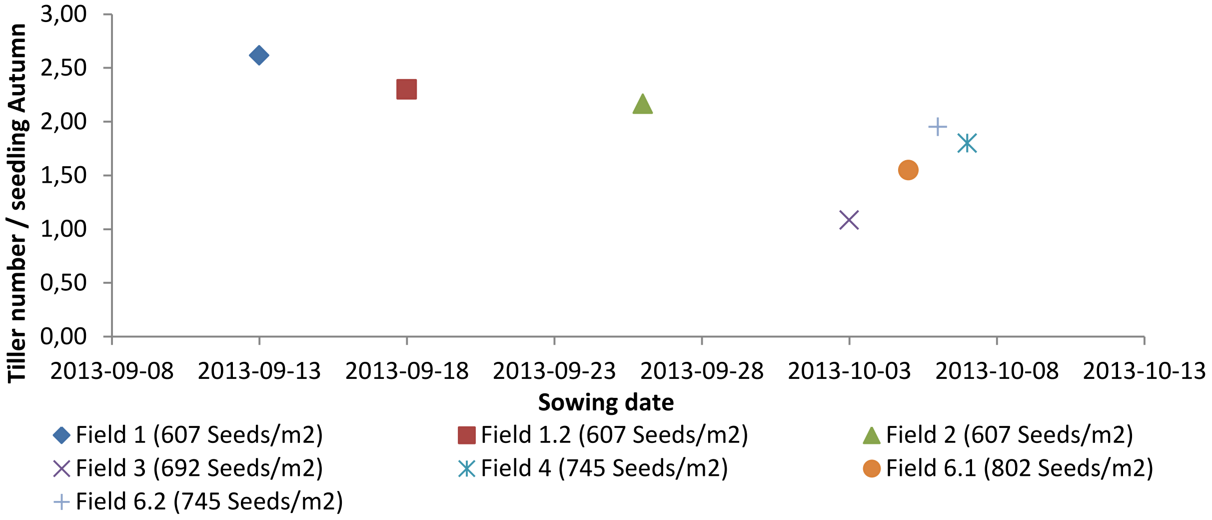


Figure 23. Tillering freqcency in April as function of sowing date.

The biomass weight per seedling at Ultuna was 0,106 grams which corresponds to winter wheat seedlings sown in 18/9 in field 1.2 in Berezan, see table 7 and 6. The Swedish seedlings were in general more compact than the Ukrainian with shorter leaves. Field emergence of 63 % in Uppsala was comparable with fields with low emergence in Berezan but with lower plant number due to lower seed rate. The winter survival was good in Uppsala. The total number of shoots was equal comparing autumn and spring. No seedlings had died during winter and no new tillers were developed in spring since the growing season had not begun when the spring examination of the plant stand was done.

Table 7. Collected data from Ultuna, Sweden. Grain yield and thousand kernel weight were harvested and measured by the department of Soil and Environment at the Swedish University of Agricultural Sciences

Field	Grain Yield	Tkw	Biomass	Plants m^{-2}		Shoots m^{-2}		Tillers	
	(kg ha^{-1})		(g/seedling)	Autumn	Spring	Autumn	Spring	Autumn	Spring
Ultuna	7200	36,9	0,106	280	278	784	780	1,8	1,8

4.2.2 Yield in fields with different sowing date and varieties

To be able to compare different fields with each other, the yields and individual yield components of normal and additional fertilization treatments were used. From the comparison of the fields it can be noted that field 1.1 had the significantly lowest yield level and field 4 the highest, see table 8 on next page.

Table 8. Mean values from the fertilization trial (emerging of NF and NF+40). Variance analysis are made on the values from fields with sufficient amount of repetitions. Values that are not followed by the same letter are significantly different (p<0.05)

Field	Grain yield	Ears	Tkw	Ear size	Kernels m^{-2}
1.1	5769 (e)	689 (a)	45,0 (cd)	17,9 (c)	13277 (cd)
1.2	5947 (de)	544 (b)	49,6 (ab)	21,6 (bc)	11800 (d)
2	7339 (b)	564 (ab)	52,6 (a)	23,6 (abc)	13601 (c)
3	7235 (bc)	590 (ab)	48,4 (cb)	25,8 (ab)	14820 (cb)
4	8729 (a)	645 (ab)	46,8 (bcd)	29,1 (a)	18679 (a)
6.1	7874 (b)	636 (ab)	49,6 (ab)	25,5 (ab)	16058 (b)
6.2	6516 (cd)	654 (ab)	44,1 (d)	23,2 (ab)	14785 (cb)

The yield levels in studied fields are in general significantly different from each other. Regression analyses in figure 24 and 25 show the correlation between yield level and ear density and ear size, respectively.

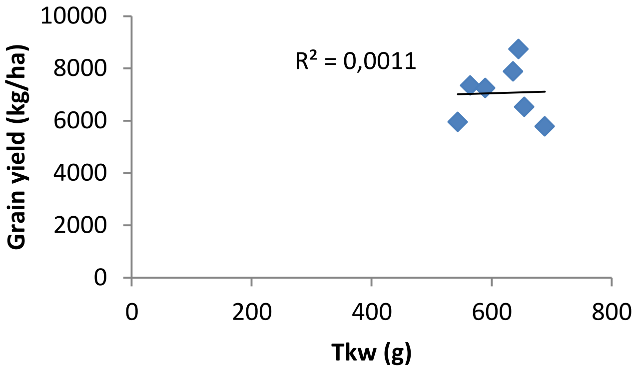


Figure 24. Yield levels as function of ear density per m^2, with coefficient of determination , R^2.

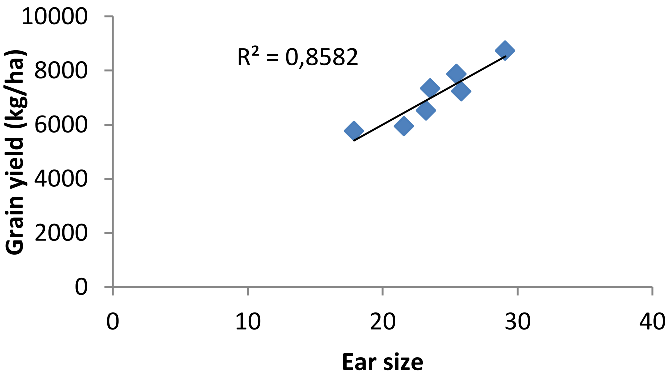


Figure 25. Yield levels as function of numbers of kernels per ear, with coefficient of determination , R^2.

There is no correlation between ear number density and yield. On the other hand the correlation between ear size and yield level for the different fields is strong. The grain population density also has a quite strong correlation as it is a function of ear density and ear size (kernels/ear). Grain size (thousand kernel weight) has no significant correlation to yield level.

It is worth to notice that field 1.1, 1.2 and 6.2 suffered from lodging.

Yield levels in trials are compared with average harvested dried yields by Grain Alliance in each field in table 9.

Table 9. Varieties, sowing date, yield and average yield in the region for the individual variety for the different fields in the study.

Field	Variety	Sowing date	Yield, tons ha^{-1} (NF*)	Yield, field level, tons ha^{-1} **	Average yields per region tons ha^{-1} ***
1.1	*Poliska-90*	(13/9)	6,08	6,10	5,81
1.2	*Poliska-90*	(18/9)	6,10	6,10	5,81
2	*Poliska-90*	(26/9)	6,96	5,72	5,81
3	*Analog*	(3/10)	7,30	6,03	6,03
4	*Sonechko*	(7/10)	8,70	6,38	6,02
6.1	*Skagen*	(5/10)	8,05	5,86	7,39
6.2	*Sonechko*	(6/10)	6,30	5,61	6,02
7 (Ultuna)	*Olivin*	(9/7)	(-)	7,20	5,3 ****

* (NF, Normal fertilization level, 160 kg N)

** (Yields reported on field level 2014, data from Grain Alliance and SLU)

*** (Average yields for different varieties grown by Grain Alliance in Kiev region 2014, average yields for winter wheat in Uppsala 2014 not available)

**** (Average yield in region of Uppsala 2004-2013, SCB)

In general the yield level is higher for the trial than the harvested yield in the entire field. In field 1.1, 1.2 and 6.2 the difference is quite small between trials and average field based yields but in other fields there was a larger difference. Average yield of Sonechko in the regionof Berezan did not correspond to the yield level in field 4. Yield level of Skagen was low in field 6.1, but in other fields not included in this study Skagen had an average yield of 7,39 ton ha^{-1} which is a lot higher than other varieties.

4.3 Fertilization trial

4.3.1 Result of fertilization trial (full set)

The yield levels from different fertilization treatments are presented in table 10. The table is based only on field 3-6.2 where full scale trials were performed

Table 10. Mean values from the fertilization trial. Variance analysis are made on the values from fields with sufficient number of repetitions, field 3-6.2. Values that are not followed by the same letter are significantly different ($p<0.05$)

Treatment	Grain yield (14% Water)	Ears	Tkw (g per 1000 kernels)	Ear size (Kernels per ear)	Kernels m^{-2}
A	7000 (a)	597 (a)	47 (a)	25 (a)	14939 (b)
B	7234 (a)	620 (a)	44 (a)	26 (a)	16377 (ab)
C	7756 (a)	596 (a)	45 (a)	29 (a)	17415 (a)
D	7585 (a)	645 (a)	47 (a)	25 (a)	16067 (ab)
E	7593 (a)	617 (a)	47 (a)	27 (a)	16104 (ab)
F	7432 (a)	633 (a)	45 (a)	26 (a)	16506 (ab)

There were no significant differences between the fertilization treatments except a lower kernel population density in treatment A and a higher in treatment C. Trials comparing time of fertilizer application (treatment C and D) showed no significant effect of applying all nitrogen fertilization in spring compared to split application with some in fall and the rest in spring.

Field 1.1, 1.2 and 2 was excluded from table 10, as only treatment D and E were included in these fields. In general these fields also yielded less than the other fields, especially field 1.1 and 1.2. It should be mentioned that crop lodging occurred in many fields but especially severe in the fertilization trials in field 1.1 and 1.2 but also in field 6.2.

In figure 24 results are presented for each individual field. There was no clear pattern of yield correlated to the amount of fertilizer. Field 3 and 4 have a trend of increased yields with increased nitrogen level but field 6.1 and 6.2 have almost an inverse correlation.

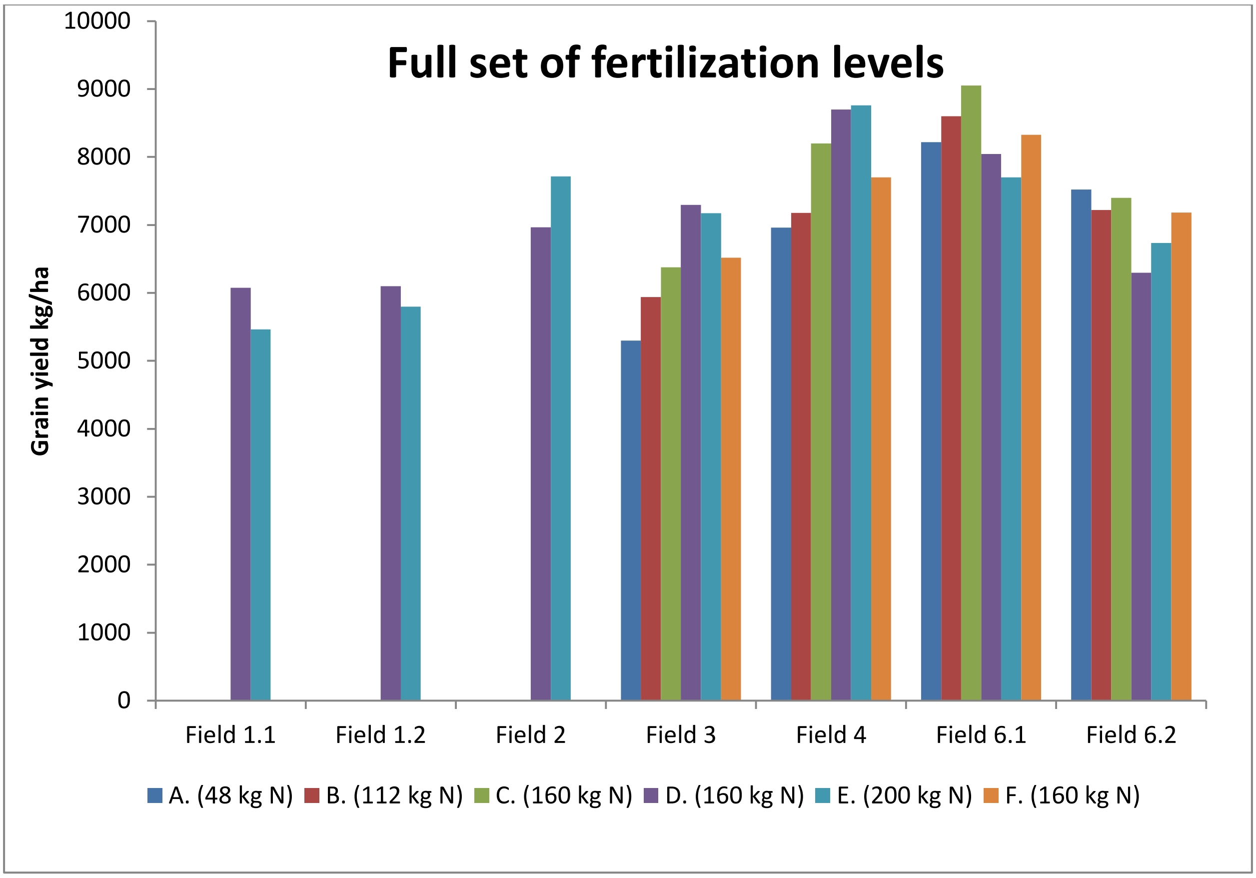


Figure 24. Grain yield levels in all fields for all fertilization treatments.

4.3.2 Comparison of fields with normal and additional fertilization

There was no significant difference between the normal fertilized treatment (treatment D, 160 kg N ha^{-1}) and treatment E (200 kg N ha^{-1}), see table 11.

Table 11. Mean values from the fertilization trial (NF and NF+40). Values that are not followed by the same letter are significantly different (p<0.05)

Treatment	Grain yield (14% Water)	Ears m^{-2}	Tkw (g per 1000 kernels)	Ear size (Kernels per ear)	Kernels m^{-2}
D	7068 (a)	627 (a)	48 (a)	24 (a)	14710 (a)
E	7049 (a)	607 (a)	48 (a)	24 (a)	14724 (a)

Additional fertilization had no significant effect on the individual yield-forming factors; ear number, tkw, ear size and kernel number m^{-2}. In four of the fields an increased fertilization resulted in a lower yield while in three of the fields it led to a yield increase.

4.4 Profile excavation

The result of the different measurements; earthworm presence, aggregate size, determination of compaction zones, root depth and roll/thread test is viewed in Table 12. None of the fields had any high presence of earthworms, however, there were wormholes to a great depth in all the fields. The soil profile in field 1.1 and 3 in Ukraine had no had no clear aggregate structure even though it largely consisted of very small aggregate particles. The clay on Ultuna had a fine aggregate structure with aggregate size between 6 and 10 mm in the topsoil, see profile pictures in figure 25.

Figure 25. ***Soil horizons of the three soil profile excavations, from left to right: field 1 and 3 in Ukraine and from Ultuna in Sweden. Source: Mats Magnusson and Jakob Eriksson.***

At Ultuna a compaction zone of the soil profile could be identified on a depth of 25-30 cm, but this was not obvious in the Ukrainian fields. The root depth varied between the different fields. In field 1.1 roots were found to a depth of 150 cm, possibly the roots grew even deeper as the profile pit not was dug deeper than 150 cm. The soil profile and texture of field 3 was comparable with field 1.1, but with some less extensive rooth depth at about 120 cm. At Ultuna the root depth was measured to 100 cm on the 15th of May when the first profile measurements were conducted, see table 12. Humus content seemed to decrease gradually with the depth in field 1.1 and 3, see figure 27.

Table 12. Earthworm presence, aggregate size in topsoil, presence of plow sole and root depth for fields 1.1, 3 and Ultuna.

	No. Earth worm	Aggregate size (mm)	Plow sole (cm)	Root depth (cm)
Field 1	1	(1-6)	None	>150
Field 3	0	(1-6)	None	120
Ultuna	1	(6-10)	(25-30)	100

The result of soil texture analysis in field 1.1 and 3 in Berezan and literature values from Ultuna is presented in table 13. According to the USDA soil taxonomy the soil at Ultuna is classified as a silty clay and the soil in field 1.1 and 3 as silt loam. Texture measurements of the Ukrainian soils determined the clay content to 16 % combined with silt of quite uniform size, ranging from fine to medium coarse.

Table 13. Texture analyze with fraction in percentage for fields 1.1, 3 and Ultuna. The values are an average from both topsoil and subsoil. The value from Ultuna is collected by the department of Soil and Environment at the Swedish University of Agricultural Sciences

Texture analyze (fraction in %)	Clay	Fine Silt	Medium Silt	Sand	Gravel	Humus content
Diameter limits (mm)	<0.002	0.002-0.02	0.02-0.2	0.2-2	2-20	%
Field 1.1 and 3	16	19	58	3,5	0	3,5
Ultuna	48	27	18	2	0	5

Dry bulk density (ρd) is presented in Table 14, for fields 1.1 and 3 where bulk density measurements were carried out and for Ultuna, where bulk density values were acquired through literature. The tests indicates that field 1.1 had a higher compaction in both the topsoil (10-15 cm) and in the subsoil (40-45 cm), than field 3.

Table 14. Measured bulk density by cylinder samples in field 1.1 and 3. The value from Ultuna is measured by the department of Soil and Environment at the Swedish University of Agricultural Sciences

Field	Bulk density (ρd)	
	(10-15 cm)	(40-45 cm)
1.1	1,583	1,457
3	1,501	1,294
Ultuna	(-)	1,475

The volumetric amount of water in the soil was calculated with the bulk density value of 1.4 g cm^{-3} as an average of subsoil bulk densities from field 1.1 and 3. In table 15 an average bulk density of 1,4 g cm^{-3} is used for calculation of wilting point in terms of volume-% water content. No measurements of these soil properties were done at Ultuna, instead values from literature is used for further calculations.

Table 15. Wilting point from measurements for Berezan . Literatur values for Ultuna.

Soil	Wilting point weight-%	Bulk density	Wilting point vol%	Wilting point vol %, based on literature
Top soil Berezan	8,08	1,4 g cm^{-3}	11,3	7,5 (at 1,3 g cm^{-3})*
Sub soil Berezan	8,84	1,4 g cm^{-3}	12,4	7,5 (at 1,3 g cm^{-3})*
Top soil Ultuna	(-)	(-)	(-)	23 (at 1,48 g cm^{-3})**
Sub soil Ultuna	(-)	(-)	(-)	29 (at 1,52 g cm^{-3})**

* Andersson & Wiklert, 1972.

** Andersson & Wiklert, 1983.

The calculated water content was compared with the values from the equipment used for water content measurements for the three different sites, see table 16, 17 and 18. At the first time for measuring (12th April), the results from the equipment and dried samples seemed to be most comparable when a bulk density value of 1,3 g cm^{-3} was used. At the second measuring time (18th June) the measured value seemed to be between the two calculated values in field 1.1 but in field 3 the calculations based on a bulk density of 1,3 g cm^{-3} was still best correlated. In the calculation of plant available water in Berezan the wilting point was set to 12 % according to the soil sample measurements.

Table 16. Volumetric ***water content in percent to the depth of 150 cm in field 1.1. Measured with two methods; soil samples and moisture meter. At the first water content measurement, the winter wheat was in DC 21-23 and at the second measurement in DC 80-85***

	(12/4) Earth sample		(12/4) Moisture meter	(18/6) Earth sample		(18/6) Moisture meter
Depth:	ρd (1,45)	ρd (1,30)		ρd (1,45)	ρd (1,30)	
10 cm	22,0	19,7	16,3	20,4	18,3	21,2
20 cm	24,4	21,9	19,3	20,2	18,1	19,3
30 cm	20,4	18,3	20,9	19,8	17,7	19,0
40 cm	22,1	19,8	18,6	19,5	17,5	17,8
50 cm	25,3	22,7	22,2	20,0	17,9	18,3
60 cm			20,4	19,3	17,3	18,2
70 cm	21,4	19,2	19,1	19,7	17,7	18,1
80 cm			20,1			19,4
90 cm	26,7	23,9	19,7	23,4	21,0	17,6
100 cm			18,9			20,0
110 cm	25,4	22,8	19,3	19,5	17,5	19,2
120 cm			17,5			18,9
130 cm	17,2	15,4	18,0	21,6	19,3	17,9
140 cm			17,4			18,8
150 cm	16,8	15,1	15,8	18,9	17,0	19,0
Mean	23%	20%	19%	20%	18%	19%
Available water	11%	8%	7%	8%	6%	7%
Water storage mm, in 150 cm	165	120	105	120	90	105

The water content in field 1.1, based on the moisture meter was 19 % in both mid-April and mid-June which would contribute to 105 mm plant available water, if root depth is considered to be 150 cm. There are just small differences between field 1.1 and field 3, comparing soil water contents measured by the soil moisture meter, see table 16 & 17.

Table 17. Volumetric ***water content in percent to the depth of 150 cm in field 3. Measured with two methods; soil samples and moisture meter. At the first water content measurement, the winter wheat was in DC 21-23 and at the second measurement in DC 80-85***

	(12/4) Earth sample		(12/4) Moisture meter	(18/6) Earth sample		(18/6) Moisture meter
Depth:	ρd (1,45)	ρ (1,30)		ρd (1,45)	ρd (1,30)	
10 cm	21,3	19,1	20,7	23,9	21,4	21,9
20 cm	27,8	24,9	24,2	23,4	21,0	21,7
30 cm	26,9	24,1	25,7	25,3	22,7	19,7
40 cm	25,5	22,9	24,3	23,7	21,3	17,8
50 cm	26,3	23,6	23,5	23,3	20,9	18,1
60 cm			23,5	23,0	20,7	16,5
70 cm	25,3	22,7	21,7	26,2	23,5	17,6
80 cm			22,0			17,6
90 cm	25,3	22,7	20,9	25,6	22,9	15,7
100 cm			20,0			16,1
110 cm	19,2	17,2	18,9	23,5	21,1	15,0
120 cm			18,8			16,4
130 cm	17,8	16,0	17,8	22,4	20,1	16,2
140 cm			17,2			18,4
150 cm	20,0	17,9	15,8	20,9	18,7	17,5
Mean (1,5)	23%	21%	21 %	24%	21%	18%
Available water	11%	9%	9%	12%	9%	6%
Water storage mm, 150 cm	165	135	135	180	135	90

At Ultuna the calculated water content based on dried soil samples shows higher soil water contents than the measuring equipment does. The ground water was observed at 1,35 m depth in May and the profile was quite wet, see values in table 18. As an average in the calculation of plant available water at wilting point to a depth of 1,2 m, it about 28 % and is used for calculation. Total amount plant available water see figure 18 on next page.

Table 18. Volumetric ***water content in percent to the depth of 150 cm at Ultuna. Measured with two methods, earth samples and moisture meter. At the first water content measurement, the winter wheat was in DC 21-22 and at the second measurement in DC 41-45***

Depth:	(15/5) Earth sample ρd (1,475)	(15/5) Moisture meter	(5/6) Earth sample ρd (1,475)	(5/6) Moisture meter
10 cm	41,9	34,3	-	31,2
20 cm	40,9	34,6	-	29,4
30 cm	40,1	33,3	-	30,0
40 cm	39,0	33,6	-	31,7
50 cm	33,1	33,4	-	27,6
60 cm	37,5	35,1	-	29,2
70 cm	38,1	34,1	-	30,6
80 cm	-	40,1	-	35,3
90 cm	44,0	38,9	-	36,3
100 cm	-	39,4	-	38,4
110 cm	50,0	40,4	-	35,4
120 cm	-	40,7	-	39,3
130 cm	52,8	44,4	-	40,4
140 cm	-	47,6	-	40,6
150 cm	-	56,0	-	-
Mean (1,2 m)	41 %	36%		33%
Available water	13%	8%		5%
Water storage mm, 120 cm	156	96		60

4.5 Phenology Model

Phenological development was simulated for three growing seasons in Ukraine and two in Sweden, these are presented in table 19. In order to more easily see the differences between years and places, the number of days of each development stage is presented in table 20. Growing season 2013-2014 in Berezan is distinguished from the two previous seasons in Berezan, in that way that every development stage except for ear emergence to the end of flowering are longer than in previous years. The total growing period 2013-2014 was almost 50 days longer than 2012-2013 and more than 30 days longer than 2011-2012. The simulated period from the start of development until maturity 2013-2014 at Ultuna was even longer than the period in Berezan for the same year, approximately 30 days, which is the same difference comparing this period 2002-2003 and 2013-2014 in Uppsala. The date for floral initiation should not be interpreted as start of growth, as it is just a development stage and not visible growth. Cold weather after this stage may delay the visible growth by several weeks.

Table 19. Dates for different development stages for four different growing seasons and at two different locations, Berezan (Ukraine) and Ultuna (Sweden). The values are simulated from a simplified phenology model by Henrik Eckersten (2003), which originally was calibrated for winter wheat in 2002-2003 at Ultuna.

	Ukraine (Berezan)			Uppsala (Ultuna)	
Phenology stages	2013-2014	2012-2013	2011-2012	2013-2014	2002-2003
Floral initiation	2014-02-22	2013-04-04	2012-03-19	2014-02-16	2003-03-17
Double ridge	2014-04-17	2013-04-28	2012-04-21	2014-04-24	2003-05-09
Terminal spikelet	2014-04-26	2013-05-05	2012-04-29	2014-05-12	2003-05-21
Ear appearance	2014-05-17	2013-05-20	2012-05-13	2014-05-31	2003-06-07
End of Anthesis	2014-05-29	2013-06-03	2012-05-28	2014-06-15	2003-06-24
Grain fill start	2014-06-01	2013-06-05	2012-05-31	2014-06-26	2003-06-27
Grain fill stop	2014-06-29	2013-06-25	2012-06-22	2014-07-24	2003-07-25
Maturity	2014-07-05	2013-06-29	2012-06-28	2014-07-29	2003-07-30

Table 20. Number of days for different development stages for four different growing seasons and at two different locations, Berezan (Ukraine) and Ultuna (Sweden). The values are simulated from a simplified phenology model by Henrik Eckersten (2003), which originally was calibrated for winter wheat in 2002-2003 at Ultuna.

Phenology stages	Ukraine (Berezan)			Uppsala (Ultuna)	
	2013-2014	2012-2013	2011-2012	2013-2014	2002-2003
Floral initiation to double ridge	54	24	33	67	53
Double ridge to terminal spikelet	9	7	8	18	12
Terminal spikelet to Ear appearance	21	15	14	19	17
Ear appearance to end of Anthesis	12	14	15	15	17
End of Anthesis to grain fill start	3	2	3	11	3
Grain fill start to stop	28	20	22	28	28
Grain fill stop to Maturity	6	4	6	5	5
Sum of days	133	86	101	163	135

5 Discussion

5.1 Sowing date

In the fields with different sowing dates, we obtained more well-developed seedlings (more tillers) in the early sown fields, which is in line with the principal of thermal time for development where the early sown wheat have reached higher heat sums. According to literature, for example Fowler (1982), earlier sown and well established wheat in DC 21-22 is more winter hardy than less developed plants. In this study no differences were found in overwintering between early sown fields (DC 21-24 before winter) compared to late sown (DC 13 before winter). The reason why we did not see any difference in overwintering between the early and late sown fields was probably because the winter 2013/2014 was mild and the growth started early in the spring. Late sown winter wheat produced tillers during spring but these were all aborted. This confirms the results from studies showing that spring produced tillers have low potential to survive jointing in dense plant stands (Spink, 1999; Thiny *et al.* 2002).

Plant number was lower but the number of tillers was higher in early sown fields. Regarding the sowing rates, it should be noted that they were generally high already at the early sowing dates and increased as the sowing was postponed. This resulted in dense stands regardless if the field was sown late or early. Given the high seed rates, virtually no tillers became ear-bearing in the late sown wheat, and for the earliest sowing dates the ear number per plant varied in the interval of 1,2-1,9. It is difficult to estimate the effect of sowing date on crop yield since different varieties were grown, but also depending on crop lodge damages in some early sown fields. We believe that the high sowing rate have had a negative effect on the ear size in line with studies for example by Gooding *et al*. (2002). If a lower plant stand density could have produced a higher yield through fewer but perhaps greater ears is not possible to confirm as no fields with low seed rates were studied. As all fields managed to produce relatively high ear numbers and kernel weights, the ear size was the harvest factor that was decisive for yield variations.

5.2 Nitrogen fertilization

In the trials with different fertilization levels, we could observe a trend for higher grain yield with increased nitrogen fertilization (although not statistically significant), from 48 to 160 kg of nitrogen per hectare. The fertilization level with additional 40 kg N (200 kg ha^{-1}) did not indicate any increase in grain yield. In line with numerous studies and as stated by Hay and Walker (1989); as long as nitrogen is a limited resource, additional nitrogen will increase the biomass and grain harvest linearly until the nitrogen effect wears off and a plateau is reached. Additional fertilization only increases the protein content, and can even lead to a decrease of dry matter and grain yield. We believe this might have been the case, and the highest fertilizer level (treatment E) might have had a higher protein level, although it is not possible to show since protein content was not measured. Most remarkable about the different fertilization levels is not that we did not see any yield increase between 160 and 200 kg N ha^{-1}, but the fact that an increase in fertilization from 48 to 112 and 160 kg N ha^{-1} only gave an increase in yield of on average 234 and 756 kg ha^{-1}, respectively. In field 3 and 4 there was a quite evident yield increase in the fertilization interval from 48 to 160 kg N ha^{-1} with about 1500-2000 kg higher yield in treatment C than in A. But in field 6.1 and 6.2 there was no yield increase or an inverse relation with highest yield for the lowest nitrogen rates. A possible reason is that these fields were by mistake improperly fertilized by the labour of Grain Alliance. Still there was a high yield in field 3 and 4, 5300 and 7000 kg grain at 14% humidity, which indicates that soil must have provided the wheat with significant amounts of nitrogen. The amount of nitrogen available in the soil vary during the season and between years with different conditions (Vaidyanathan, 1984). As measurements of soil nitrogen and grain protein content not were conducted, we can unfortunately not confirm the nitrogen supply and uptake. If there is generally no, or just low, outflow of water from the soil profile, nitrogen can be stored over seasons too, which often can be the case in Kiev region.

We were not able to see any clear correlation between fertilization and harvest-building factors (ears m^{-2}, kernels per ear or kernel weight) in the fertilization trials. We were expecting to see more ears per m^2 and more kernels per ear in the plots with higher fertilization levels according to Gooding *et al*. (2002). The reason why we did not have any significant effect on the number of ears is probably the high sowing rate, which resulted in a very dense stand and that no tillers could survive even if they had a greater access to nitrogen. In the case of kernels per ear, we have no significant differences but there may be a tendency for more kernels per ear in the plots with increased nitrogen fertilization. Different features of varieties are a probable reason to variation of the ear size between studied fields, and make it less probable to find significant variations between fertilization treatments. Low number of repetitions and crop lodging damages are also sources of error.

The fertilization strategy applied during the growth season 2014, with fall fertilization, early spring fertilization and one complementary fertilization, has worked with acceptable results. It should be mentioned that autumn fertilization increases the risk of nitrogen leaching in wet winters as the wheat just utilize very little nitrogen in the autumn (Hay & Porter, 2006). In dense well established stands in spring there is no need for of a lot of early available nitrogen and there is therefore no need of a very early fertilization (Cui *et al.*, 2010). The early nitrogen application in Grain Alliance wheat cultivation was not motivated from a crop perspective, but in order to reduce ammonia losses and leaf burns from the UAN fertilizer early application is preferable (Johnston & Fowler, 1992). The total amount of nitrogen must be adapted to the target yield level and quality, in terms of protein content. Depending on whether the wheat will be sold as bread wheat or animal feed, the final protein content is crucial. The total nitrogen fertilization of 160 kg N ha^{-1} provides a good, almost excessive, margin of bread quality in the field (varieties) that only generated a yield of about 5 tons. On the other hand fields (varieties) which yielded over 8 tonnes were at risk of having a too low protein content due to the dilution effect (Marte *et al.*, 2003) if the mineralization from the soil has not been exceptionally high (Goulding, 1990). Protein content measurements were not available for each field but have varied in the range 10-12,5 % according to Zaglada[1],

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[1] Zaglada, Evgeniy; Head of planning-economic department Grain Alliance. 2014. E-mail, 2014-12-12

2014. It indicates too low nitrogen fertilization in some cases to fulfill the requirements of bread quality wheat in some cases.

To split the fertilization in to two or three applications is preferable to adjust the nitrogen rate to the optimum levels of each year according to plant stand development and weather conditions. This might led to higher application costs and some time the risk of non-available nitrogen if the weather is dry and not contribute to infiltration of nitrogen, but in general it contributes to a more sufficient fertilization rate. The risk of leakage is also reduced and it facilitates to apply sufficient amount of nitrogen to meet the protein requirements (Wuest & Cassman, 1992). Example of measures to continuously evaluate fertilization actions is none fertilized areas in field to estimate mineralization of the soil, and according to that adjust the amount of nitrogen for application. Another opportunity is to do nitrogen tests in spring to measure the amount of available nitrogen in soil, but these soil tests are generally not always so significant as mineralization during season often is more important than the amount available in early spring (Egil Persson, 2002).

5.3 Phenology Model

By using a phenology model we got a fairly good idea of how the temperature and day length affected the duration of different development stages from growth start until maturity. The phenology of winter wheat in Berezan 2014 compared to Uppsala shows a shorter period of growth in early spring in Berezan. Tillering is mainly dependent on temperature, moderate temperature and relatively short days therefore gives a more extensive tillering as higher heat sums can be reached before stem elongation starts and tillering ends (Hay & Porter, 2006). High temperature during jointing decreases the survival of tillers as the competition of resources gets intensified with faster development (Bean & Duncan, 2011). This is probably one reason for extensive tiller reduction in the Ukrainian wheat, but also a function of dense stands. In relation to the growth seasons of 2012 and 2013 in Berezan the vegetation started earlier and the grain filling period lasted longer in 2014, and might be reasons to higher yield level this year. The model has also highlighted that the high temperature around mid-May and early June accelerated the development so that ear size probably was reduced, in line with studies of Fischer (1985). During this period the daily average temperatures exceeded 20 ˚C and the daily maximum temperatures of 25-30 ˚C. This has probably caused some reduction of spikelets and lower ear growth with fewer flower buds that could be fertilized. Overall, this has likely led to a reduced yield potential. High temperatures during grain filling reduces the duration of the event and the potential starch deposition to the kernels, which leads to reduced kernel size and yield in a stand with high grain population density (Egli, 1998). In 2014 the duration of grain filling period was relatively long and the kernel size normal to high as well. Grain filling will probably be quite complete, in terms of kernel size, in years with shorter grain filling period, if the grain population density is low according to Wardlaw & Wallenbrink (2000), but these still result in a lower yield.

5.4 Soil and water properties

Precipitation in the Kiev region is higher than in the Uppsala region, but due to higher temperatures during the growing season the potential evapotranspiration is higher as well. According to the general patterns of Kiev region, the highest amount of precipitation falls in the period from May to August. Unfortunately the winter wheat cannot benefit from all of the precipitation as the winter wheat normally starts maturing in the end of June. On the other hand early maturing wheat does not suffer from potential drought during July when temperature and evapotranspiration are the highest.

The soil properties in the studied fields in Berezan are very favourable for crop production. Optimum bulk densities for crop production is mentioned as 1,2-1,3 g cm^{-3} (Mamsirov *et al.*, 2013). Our measurements showed relatively low bulk density in the subsoil, 1,29-1,46 g cm^{-3}, (the more compacted soil is collected from a highly trafficked part of the field) which is quite suitable for root growth. Good soil physical properties for root growth was demonstrated by root depths of more than 1,5 m. The high content of silt gives a relatively good percolation but also water holding capacity combined with aeration of the soil. The amount of plant available water at field capacity is quite similar for the Ukrainian silt soil and a Swedish clay soil according to our calculations, but the water content at both the wilting point and at field capacity is lower for the silt soil compared to the clay. In a Swedish climate with excess of precipitation and ground water table at drainage depth the silt soil would hold much more plant available water than a clay. But for this region of Ukraine the groundwater table was estimated to 4 m which gives a field capacity of 27 vol % water. If the ground water instead had been set on 1 m depth, which is common in Sweden, the soil water content at field capacity would have been 37 vol%. Under such conditions the soil could supply a crop even better with water. Wilting point of the Ukrainian silt soil was measured to 12 vol % while it was 28 % at Ultuna, but the Ultuna soil can hold about 42 % water at field capacity in the subsoil. So both soil can retain 140-150 mm plant available water per meter soil profile. Potentially greater root depth on the silt soil increases the total amount of plant available water for the wheat. On the other hand a less humid climate in Ukraine makes it less common with field capacity in spring and the amount of available water is therefore often reduced. With effective root depth of 1,5 m in Berezan and 1,2 m at Ultuna the estimated amount plant available water is 225 mm and 168 mm, respectively at field capacity. With a precipitation of 175 mm in Berezan during wheat growth period (April-June) and 176 mm at Ultuna (April-July) the total amount of available water is 400 mm and 344 mm respectively, provided that both soils have reached field capacity at the start of growth season. Compared to measured potential evapotranspiration of 350 mm in a climate comparable with the Kiev region during April to June, and 383 mm in Uppsala during April to July both growing sites seem to have sufficient amount of water to not suffer from drought (Svitlychnyi *et al.*, 2010; Wallén, 1966). Still droughts can occur in both the Kiev region and Uppsala region as weather conditions vary between years, and distribution of precipitation during the year. According to this estimation, the Kiev region seemed to have less risk of droughts than Uppsala. But it is important to notice that the estimated soil water storage not always become filled during the autumn/winter in Ukraine, while it normally does in Uppsala. This Ukrainian loess soil is easy to cultivate, and gives good opportunities for seed germination due to a relatively low wilting point and good capillary properties. This soil with good seed germination motivates a lower amount of seed for sufficient field emergence compared to clay soils with coarse structure in the soil surface (Håkansson *et al.*, 2011) This kind of soil is not so sensitive to crusting and poor aeration (Baumhart *et al.*, 2004). The lower specific draft requirement for tillage on a loam comparing to a clay according to Arvidsson & Magnusson (2010) gives opportunities for tillage machinery with larger working width and lower operations costs in Ukraine.

5.5 Adaption of cultivation to climate

During winter months the Kiev region of Ukraine is normally covered with snow that makes it less sensitive to periods of severe cold than southern and eastern parts of Ukraine, where it normally is less common with snow coverage. In the winter 2013/2014 cold events occurred during periods of snow coverage that protected the wheat plants, and probably contributed to a very good overwintering of the wheat. Still damage of winter wheat stands occurs occasionally in Ukraine due to severe cold and weak snow coverage (Lazar, 2005). Winter hardiness is therefore an important factor for wheat varieties to become successful for cultivation in these parts of Ukraine.

The more intensive temperature increase in spring in central Ukraine compared to southern Sweden makes the crop development faster. The ability to produce tillers in the spring vary between years, but is not so reliable as temperature some years rise rapidly after the growth start in spring, which reduces the tillering frequency and tiller survival according to Acevedo (1991). To achieve a desired plant stand density with sufficient number of tillers, seed rate and sowing date is therefore very important as spring tillering is not reliable.

High temperatures during spring and summer reduce the yield potential as each plant does not grow as vigorous and each spike is reduced in size (Porter & Gawith, 1999). A sufficient density of ears/m^2 is important to get high yields in these conditions as the ability to compensate for sparse wheat stands by producing a greater ear per plant is lower in warmer climates compared to those of moderate temperature. In the studied fields in Berezan 2013-2014 there was relatively high (540-650) numbers of ears/m^2, and the correlation between ear number density and yield level was non-existent. Instead the correlation between ear size (number of kernels per ear) and yield level was high.

Studies show higher cereal grain yield in cultivation with narrow row spacing according to Marshall & Ohm (1987); Johnson *et al.*, (1988); Freeze & Bacon, (1990), mainly depending to higher potential ear number due to a more uniform plant stand (Andersson, 1983). The relatively wide row spacing (19 cm) and high seed rate (310-370 kg / ha) has probably affected the plants negatively. A more narrow row spacing with a uniformed plant orientation would probably generate a higher yield in Berezan, but also lead to some increased machinery cost. It is important to notice that different varieties are compared in this study. As no fields with low plant stand densities was studied it´s hard to comment if lower plant densities could have given greater ears. As there was a great variation in ear size in each trial it is probable that a less dense stand would give a homogenous plant size and in general larger ear size, according to studies of Gooding *et al*. (2002). The variation of average ear size was in the range 18-29 kernels per ear, which is a large variation. Compared to Swedish wheat cultivation the number of kernels per ear was low (Hagman *et al*. 2014). Kernel size varied between fields and varieties in the range 44-53 g per 1000 kernel. It is quite similar to reported kernel size for these varieties (Seeds of Ukraine, 2015; Hagman *et al*. 2014). We interpret this as there has been little or no heat or water stress during grain filling in the summer 2014 in Berezan. Temperature and soil water content during June, when grain filling occurred, also indicates good conditions.

Observed yields in the trials with normal fertilization was in the range 6,1-8,7 ton ha^{-1} and the harvested yields by Grain Alliance in studied fields in Berezan was in a range from 5,6 to 6,4 ton ha^{-1}. On about 280 ha in Berezan, the variety Skagen was grown but not included in the study. In these fields the yield varied in the interval 7,2-8,2 tons ha^{-1}, which indicates the potential of the yield potential for this Danish bred wheat in this studied year according to Zaglada[2], 2014. Yield statistics for 2014 for Kiev region was not available for comparison, but yield forecast according to NDVI and EVI that were conducted in end of May 2014 estimated a grain yield level of 4,5 tons ha^{-1} in the Kiev region which was one of the best regions for that year (UN-spider Ukraine RSO, 2015). High input of fertilizer, plant protection, high quality of seed and varieties for intensive cultivation and quite well managed field activities is probable reasons for higher yields in Grain Alliance wheat cultivation than the average. It is also possible that growth conditions in Berezan have been somewhat better this year than the average of the Kiev region, but is not investigated.

5.6 Crop growth modelling

The requirement of accurate input data is crucial for any crop model. Various models require different amounts of input data. Generally the simpler models require less input data, but these models often have larger margin of error. In the case of estimating winter wheat yields in Ukraine accurate input data can be difficult to get and no theoretical model can be more accurate than the data that is put in. In this work we did not use any complex crop growth models for estimating crop yield since we considered that our data was too limited for model calibration.

5.7 Sources of errors

Something that has affected the study and especially the field trials are communication difficulties. We have experienced difficulties obtaining rapid and accurate information in general and we also experienced difficulties to give instructions in an efficient way to the employees in Ukraine, especially regarding the field trials. Due to that we are not certain if the fertilization treatments have been carried out exactly according to agreement and we lost some repetitions in the trials in field 6.1 and 6.2. The field trials were adapted to the existing

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[2] Zaglada, Evgeniy; Head of planning-economic department Grain Alliance. 2014. E-mail, 2014-12-11.

cultivation and are not done as conventional field experiments, the fields (trial plots) had different sowing rates, varieties and soil properties. This meant that we have had some difficulties to compare the different fields with each other. For easier comparisons and more accurate results, the number of repetitions of trial plots should have been greater. To be able to get the best possible understanding of when the wheat´s different development stages occurs we would have had to be in Ukraine more than two times during the spring, this can also be a source of errors. The method regarding the plant count had to be changed during the study which gave problems in comparing data between autumn and spring. At last we also experienced different levels of crop lodging in our field trials, which resulted in a source of error.

6 Conclusion

The climatic conditions in central Ukraine differ from eastern Sweden mainly by higher temperatures during spring and summer, which accelerate the phenology of the wheat and reduce the grain yield potential. Overwintering is critical in both Kiev and Uppsala.

The studied soil in Ukraine has conditions for extensive root depths and relatively high potential amount of plant available water, which reduces the risk of drought stress in wheat stands. Soil water reservoir and precipitation is in average year sufficient for intensive wheat cultivation in both Kiev and Uppsala. The studied wheat fields in Berezan do not seem to suffered from drought in 2014 according to soil water measuerments, while the wheat in Uppsala might have.

Well-established winter wheat plants in the autumn are important to ensure best possible yield potential. In Kiev region the general rapid temperature increase in spring makes the plant stand even more dependent on autumn developed tillers to get a sufficient number of ears. Overwintering is also more reliable with well-established wheat plants comparing to late developed plants, according to literature, but this was not noted in this study.

The seed rate applied in Grain Alliance´s winter wheat cultivation is probably economically as well as biologically suboptimal, especially for early sowing dates in September. Still relatively dense plant stands is motivated as ear size often can be reduced by high temperatures.

In the fertilization trials yield levels were relatively high even with low fertilization, which indicates high mineralization of nitrogen or carry over effects of fertilization previous year. Fertilization rate above 160 kg N ha^{-1} gave no further yield increase in 2014. Adjustment of fertilization rates and application times is motivated to compensate for varying factors. The most important factors are the amount of soil available nitrogen, plant stand properties in spring, yield potential and aspects of quality for grown variety and amount of plant available water.

Different dates for application of 160 N ha^{-1} showed no significant variation in yield. UAN fertilizer can motivate an early fertilization in spring to reduce ammonia losses, but there is no biological gain of applying nitrogen very early in spring, as there is no need if the stand is already dense and well established.

The yield level in Grain Alliance winter wheat cultivation 2013-2014 was considerably higher than the average yields of winter wheat in the Kiev region and the whole Ukraine. An intensive cultivation management is practiced by Grain Alliance and the yield is not substantially restricted by low input of fertilizer and plant protection. For further improvements of grain yields, management factors as sowing date, seedbed preparation, seed rate, row spacing, varieties, and timing of field action, especially fertilization strategy are key factors to reach economical optimum in wheat cultivation.

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