11

Irrigation of Field Crops in the Boreal Region

Pirjo Mäkelä, Jouko Kleemola and Paavo Kuisma
Department of Agricultural Sciences,
University of Helsinki & Potato Research Institute,
Finland

1. Introduction

The Boreal region is indicated as the green areas in Figure 1, covering northern, central and southern boreal zones according to the definition of Hämet-Ahti (1981).

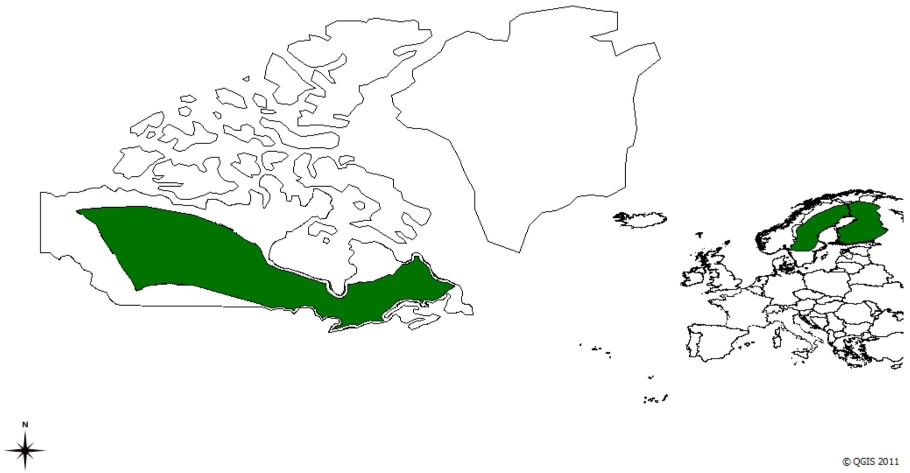


Fig. 1. The green areas indicate the Boreal region as defined in this study.

Nearly the entire agricultural area in the Boreal regions shown in Figure 1 lies in Canada (total of 68 million hectares; STATCAN, 2009). Sweden has about 2.6 million hectares (Jordbruksverket, 2011) and Finland 2.3 million hectares (TIKE, 2010). Most of Sweden's agricultural area is, however, located in the southern part of the country, outside the Boreal region.

2. Specific climate features of the Boreal region

The length of the growing season is limited by late spring frosts, early autumn frosts and solar availability in the Boreal region (Mela, 1996; Olesen & Bindi, 2002). The length of the growing season is typically 180 days in the southern areas whereas in the northernmost areas, where agricultural production occurs in the Boreal region, it is only 120 days (Mukula & Rantanen, 1987; ATLAS, 2009).

A part of the annual precipitation falls as snow in the Boreal region, a significant part of which can be lost from agricultural fields as surface runoff when the snow melts. Moreover, a part of the precipitation may be lost as evaporation or sublimation directly from snow (Perlman, 2011). Evaporation losses are considered to be small, however, at least according to a study conducted in Finland in the early 1970s (ref. Kuusisto 2010).

When estimating how much water is available for crop growth in the Boreal region, it is reasonable to divide annual precipitation into two components, as shown in the schematic water balance figure (Figure 2).

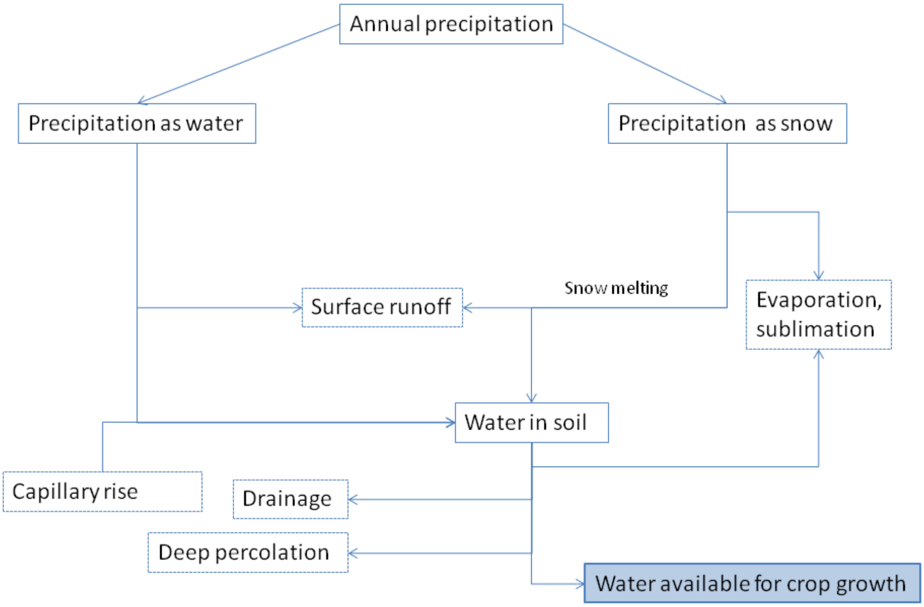


Fig. 2. A schematic representation of water balance in agricultural fields in the Boreal region.

The total volume of water available for crop growth is determined by the water-holding capacity of the soil, contributed by precipitation, minus evaporation, runoff and drainage losses during the growing season. Depending on the soil type and structure, a small volume of water can be lost by deep percolation and some can be gained by capillary rise of water from deeper soil layers. Groundwater can be a significant water resource in soils with a shallow water table (Muellera et al., 2005).

2.1 Precipitation and evapotranspiration

Annual precipitation exceeds potential evapotranspiration (measured often with Class A evaporation pan) in Scandinavia and eastern and northern parts of continental Canada (Figure 3). Thus, annual water deficit is negative in large areas within the Boreal region (ATLAS, 2007; Wallen, 1966; Ilmatieteenlaitos, 2011; Järvinen, 2007).

It has to be noted that data from Canada did not include an estimate of evaporation during the period outside the growing season. This value can be about 10 % of the annual potential evapotranspiration (Wallen, 1966). Thus, adding it into our data would result in only minor changes in Figure 3.

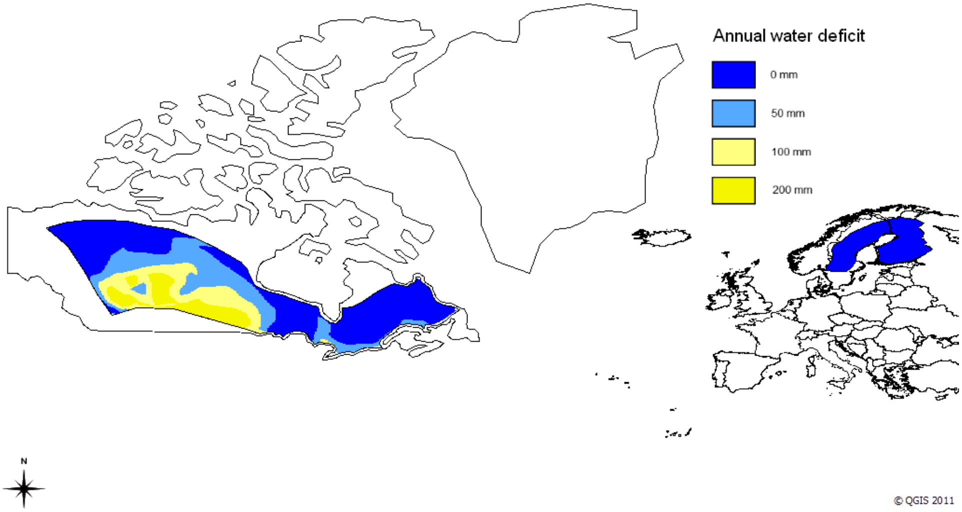


Fig. 3. Annual water deficit (potential evapotranspiration - precipitation) in the Boreal region.

Despite the annual deficit being negative in the Boreal region, it can be positive during the first half of the growing season, for example, in the period from May to July (Pajula & Triipponen, 2003): the average deficit is 100 – 250 mm in Finland during this period (Figure 4).

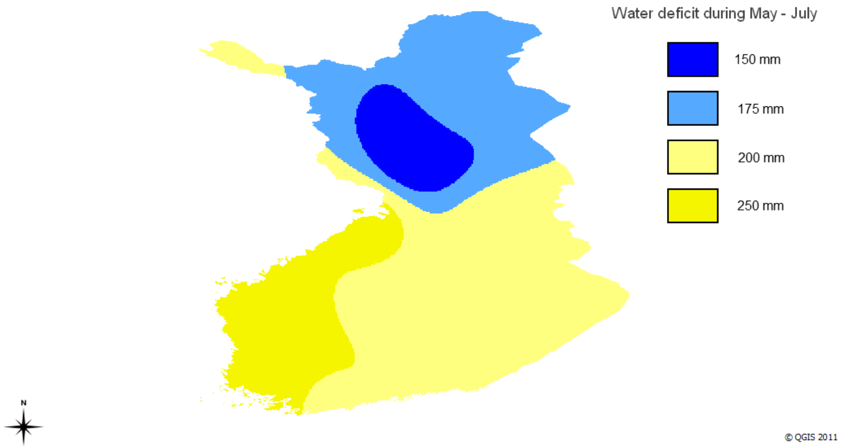


Fig. 4. Average water deficit (potential evapotranspiration - precipitation) in Finland during May - July.

The Atlas of Canada indicates that British Columbia and southern Alberta contain areas of severe moisture deficit at some times during most summers (ATLAS, 2007). Such seasonal drought affects agricultural production. For example, Hooli (1971) and Peltonen-Sainio et al. (2011) reported that early summer drought decreases yields of field crops in Finland. Spring sown crops in particular may suffer from drought during this period if soil water-holding capacity is low when root systems are not fully developed.

2.2 Spring and autumn frosts

Spring and autumn frosts represent a climatic risk for field crops grown in the Boreal region. Spring crops are sown in May and harvested in August – September, and frost during this period can damage crops.

Solantie (1980) reported detailed data for frosts in Finland. It is common to have 3 night frosts in June in southern Finland, in areas away from lakes and the Baltic Sea. Frosts are even more common in northern Finland where there can be 4 night frosts in June. It is not common to have frost in July, but in August the risk of frost increases again. The average number of night frosts is 1.5 in southern Finland and 2.5 in northern Finland.

3. Irrigation methods and possibilities

Canada has most of the irrigated field area in the Boreal region, about one million hectares, which represents about 1.5 % of the entire agricultural area in Canada (ATLAS, 2007). The irrigated area in Sweden is about 55 000 hectares (about 2 % of all agricultural land, Brundell et al., 2008) and in Finland it is 88 000 hectares (4.4 % of all agricultural land, Pajula & Triipponen, 2003).

It is not common practice to irrigate field crops (cereals, oilseed crops, potatoes, sugar beet, forage) in the Boreal region. For example, for field crops other than potato (*Solanum tuberosum* L.) and sugar beet (*Beta vulgaris* L. var. *altissima*), irrigated crops represented only 1% of the total crop area in Sweden in 2006. In contrast, the entire area of potato for processing was irrigated in 2006. Also table potatoes (59 %) and sugar beet (16 %) were irrigated fairly often in Sweden (Brundell et al., 2008). Finnish reports indicate the irrigated area to be divided between crops such as cereals and sugar beet in a similar way as in Sweden, but exact data are difficult to locate (Pajula & Triipponen, 2003). Nevertheless, the irrigated area of potato is markedly larger in Sweden than in Finland.

The situation in the Nordic region is opposite to that in Canada, where field crops comprise 53 % of the irrigated area. Feed crops are the second most common crop to be irrigated (33 % of the irrigated area). It is less common to irrigate vegetables and fruits in Canada (STATCAN, 2009).

Regardless of the application, a key set of resources determines the maximum return on investment (Holzapfel et al., 2009). At farm level, this means using available data on climate, water availability, soil, crop, economic and social circumstances, and evaluating the potential distribution system (Pláyan & Mateos 2006). Irrigation types include surface or flood irrigation, overhead, drip and sub-irrigation.

3.1 Surface irrigation

In surface irrigation, water moves over and across the land by simple gravity flow. The most widely techniques on surface irrigation are furrow irrigation and flood irrigation. These systems, however, are not common on field crops in Boreal region.

3.2 Overhead irrigation

Overhead irrigation includes different types of sprinkler and centre-pivot irrigation systems that are used to supply water in a similar way to natural rainfall (Brouwer et al., 1988) and can be used for most crops. This does not set strict constraints on the slope or soil type of the field as long as the application rate is adjusted to avoid ponding and runoff.

Sprinkler systems are used for 60 % of the irrigated area in Finland (Pajula & Triipponen, 2003) and sprinklers and pivots are used for virtually all of the irrigated field and feed crops in Canada, whereas micro-irrigation is the method most commonly used for fruits and vegetables (STATCAN, 2009).

3.3 Drip irrigation

Drip or trickle irrigation uses slow flow of low pressure, well filtered water in a (permanent) network of small diameter polythene tubes that open near the root zone (Shock, 2006). According to the location of tubes in the soil, drip irrigation can further be divided as a surface drip and subsurface drip (Sammis, 1980). According to Shock (2006) drip irrigation can be used whether the water demand is high or low.

Drip irrigation is considered to use water more efficiently than overhead systems (Shock, 2006). In an experiment on potatoes in Sweden, there was no significant difference in water use between these methods, but water use efficiency was better in the drip system, producing 11 % higher total yield and 28 % more marketable ware potato yield (Wiklund & Ekelöf,2006).

Drip irrigation is adaptable to irregularly shaped fields, it is not affected by wind, it can be designed so that the wheel traffic rows are dry to allow tractor operations at any time, and it can easily be automated (Shock, 2006). Precise application of nutrient is also possible using drip irrigation. Its disadvantages include high establishment, labour and consumables costs, as the fine tubes require inspection, maintenance and generally annual replacement (Forsman, 2006).

3.4 Subirrigation

Subirrigation is a method in which water is added below the soil surface into a controlled drainage system (Broughton, 1995), but is not as common as sprinkler irrigation. Subirrigation requires a flat field with a slope of less than 1-2% (Pajula & Triipponen, 2003) and sandy soil in which the capillary rise is high and soil permeability is sufficiently fast and uniform within a field (Geohring et al., 1995; Muellera et al., 2005). Optimum water table depth is related to soil type and crop grown on the field (Muellera et al., 2005).

Gilliam & Skaggs (1986) listed five environmental benefits that derive from using subirrigation: 1) more complete use of fertilizers, 2) reduced nutrient losses, 3) reduced leaching of pesticides and herbicides, 4) stabilized crop production and 5) more food grown on flat land, thereby removing erosion-prone land from cultivation and increasing land area for forests, grasslands, wildlife habitats and recreational uses. Moreover, farmers may benefit from increased yields due to subirrigation. Among others, the studies of Drury et al. (1996) and Madramootoo et al. (2001) support the environmental issues listed by Gilliam & Skaggs (1986). Efficient control of nutrient losses requires a dual-level subirrigation system where there are separate pipes for drainage and irrigation water. Otherwise, there may be significant loss of water and nutrients when the system is switched from irrigation to drainage mode (Melvin & Kanvar, 1995).

Subirrigation may promote substantial yield increases if the field is suited to this irrigation method. Yield increases of 20 to 40 % have been reported for maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] in humid areas (Broughton, 1995).

Subirrigation and controlled drainage could be used more in the Boreal region (Pajula & Triipponen, 2003). For example, it was estimated by Puustinen et al. (1994) that 770 000 hectares in Finland could be equipped with controlled drainage systems instead of the current 34 300 (Pajula & Triipponen, 2003). This last figure overestimates the current value of subirrigation, because although the drainage systems installed under most Finnish arable fields can fairly easily be used for water supply, this seldom happens in practice. The main barriers to using subirrigation are steepness of slope, soil types that do not transport water fast enough, and high construction costs (Pajula & Triipponen, 2003).

3.5 Availability of irrigation water

The Boreal region is characterized by areas in which there is no risk of water scarcity. Alcamo et al. (2000) determined this based on calculating the ratio of water withdrawals and water availability in different river basins. Water withdrawal includes all water that is taken from rivers/lakes, evaporation and deep percolation. Water availability is determined as a sum of annual runoff plus shallow groundwater recharge. The Boreal region has low ratio values, in the 0 – 0.1 range, which means there is enough water for domestic, industrial and agricultural use according to Alcamo et al. (2000).

Annual precipitation usually exceeds potential evapotranspiration in the Boreal region (Figure 3), which means that surface water is usually available for irrigation. This assumption is supported by a survey made in Sweden that reported surface water being the most common source (53 %) for irrigation (Brundell et al., 2008). Groundwater was used by 31 % of the farms that irrigated, and stored water was used by 16 % of the farms. However, another Swedish study reported the percentage of farms using surface water to be much higher, 80 % (Anonymous, 2007). Surface water was the most common source (37 % of the farms that irrigated) of irrigation water also in Canada (STATCAN, 2009). However, it was almost as common to use off-farm water (34 %). Underground water or well water was a fairly common source for irrigation (21 %).

Local conditions markedly affect the availability of irrigation water in a specific field. Irrigation costs increase rapidly when the distance of the field from the irrigation water source increases. The difference in altitude between field and water source has even more effect on the costs (e.g., Dumler et al., 2007). Therefore, the availability of irrigation water that is accessible at reasonable cost has to be estimated separately for each field.

4. Effect of short drought periods on crop development, growth and yield

The drought periods are usually short in the Boreal region, lasting for two to four weeks. However, in rainfed areas, even such a short period without rain can result in yield losses related to water deficit. The southern areas in Finland, especially the south and west coasts, are prone to spring droughts. The drought periods can sometimes occur after mid-summer, during the grain filling period. Boyer (1982) stated that drought is one of the most yield-limiting factors worldwide. Peltonen-Sainio et al. (2011) estimated that on average short drought periods have caused yield losses of 7-17 % in Finland within the past 30 years.

4.1 Early season drought and irrigation

Water deficit early during the season, in the spring, affects the emergence of spring-sown crops. Seeds either do not germinate or the germination processes are interrupted if there is not enough water in the surrounding soil. This results in formation of uneven plant stands (Figure 5) and causes both reduction in yield and quality. In sparse plant stands weeds have more space for growth, and for example in the case of cereals, if additional tillers are formed the grain size is reduced in them in comparison with in the main culm, and the tillers reach maturity later than those of the main culm. At later stages, during vegetative growth of cereals, water deficit affects the solar energy capture capacity of cereals, mainly decreasing the fraction of photosynthetically active radiation intercepted, but also radiation use efficiency (Olesen et al., 2000). In general, the amount of vegetative biomass at the time of anthesis is related closely to the final number of grains (reviewed in Passioura & Angus, 2010). For spring cereals, long coleoptiles and vigorous seedling emergence are important traits in Boreal conditions, where there is uneven precipitation and a short growing season (reviewed in Mäkelä et al., 2008).

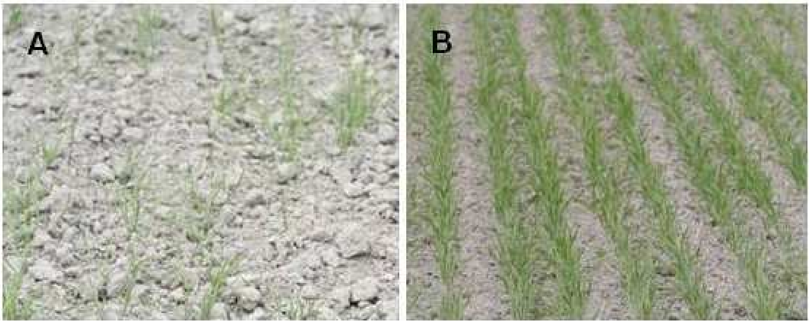


Fig. 5. Seeds germinate unevenly or germination processes are interrupted in dry soil, resulting in uneven and sparse plant stands (A). Uniform and vigorous plant stands develop when soil moisture, among other factors, is optimal for germination (B).

In spring barley (*Hordeum vulgare* L.), early season water deficit reduced both the sink and source capacity of plants through decrease in photosynthesis and thereby dry weight accumulation and number of grains (Rajala et al., 2011). According to Jamieson et al. (1995), a water deficit related decrease in dry weight accumulation of barley during the early phases of growth is mainly due to reduced radiation use efficiency, which does not recover completely after stress relief. In oat (*Avena sativa* L.), vegetative growth was limited most due to early occurrence of a water deficit, which was related to decrease in gas exchange and increase in osmolyte synthesis, e.g. proline (Peltonen-Sainio & Mäkelä, 1995).

Water deficit occurring at an early stage can, however, have more wide-ranging effects. In wheat (*Triticum aestivum* L.), pre-anthesis water deficit significantly increased floret abortion and formation of sterile florets (Rajala et al., 2009). Also, depending on cultivar, pollen fertility can decrease by over 50 % when wheat is exposed to a water deficit (Briggs et al., 1999). Saini & Aspinall (1981) reported that water deficit induced formation of shrivelled anthers and non-viable pollen. Even a short duration of water deficit at the young microspore stage induces sterility in wheat, whereas ovaries are not affected (Ji et al., 2010). Supply of assimilates seemed to be closely connected to floret abortion and formation of sterile florets (Rajala et al., 2009). In drought-stressed wheat, the sugar delivery to the reproductive organs, for example pollen grains, is limited, resulting in absence of starch (Saini & Westgate, 2000). However, Lalonde et al. (1997) stated that this was merely a consequence of earlier changes such as suppression of invertase activity, triggering sterility and delayed or premature degeneration of male cells. In small-grain cereals, determination of grain size begins already before anthesis, during sporophyte development, whereas grain number is controlled throughout spike development, at the earliest stage of male gametophyte formation (Ji et al., 2010).

Spring oilseed rape [*Brassica napus* L. ssp. *oleifera* (DC.) Metzg.] responded to early season water deficit with decreased leaf area, which was later also observed as halved dry matter by the time of flowering (Mogensen et al., 1996). The early season stress affected also the seed quality of oilseed rape, seed protein content and glucosinolate concentration increasing markedly in stressed plants (Jensen et al., 1996). The increase in glucosinolate concentration, from approximately 12 to 20 µmol g^{-1}, was in relation to plant water status, whereas the protein content probably increased after active uptake of nitrogen followed by transport into seed after growth retardation (Jensen et al., 1996). Winter turnip rape [*Brassica rapa* L. ssp. *oleifera* (DC.) Metzg.] is most sensitive to water deficit during flowering. Water deficit at the flowering stage caused over 100 growing degree days later maturity, 15 % lower seed oil content, and 64 % lower yield than in a well-watered control (Tesfamariam et al., 2010).

Cool-season grain legumes grown in the Boreal region are rather drought sensitive; faba bean (*Vicia faba* L.) being the most sensitive (F.L. Stoddard, personal communication). Furthermore, the European faba bean genotypes are more drought sensitive than genotypes from North Africa and Latin America (reviewed in Stoddard et al., 2006). The differences between genotypes in drought tolerance are marked. Some have high water use efficiency, indicating good capacity for photosynthetic maintenance and transpiration efficiency, some are able to adjust the leaf temperature, and thus stomatal conductance, more efficiently according to prevailing conditions (reviewed in Khan et al., 2010). Unlike cereals and oilseed crops, legumes have *Rhizobium* in their root nodules, which fix nitrogen. Drought limits the number of nodules in faba bean roots (reviewed in Serraj et al., 1999) and thus decreases further the nitrogen availability for the crop. All the steps of establishment of *Rhizobium*-legume symbiosis are sensitive to water deficit. This can be related to limited growth and movement of *Rhizobium* in soil during drought, thus restricting the infection process needed for nodule formation. The root hair infection and formation of infection threads is also sensitive to water deficit (reviewed in Serraj et al., 1999). Moreover, the supply of carbohydrates from the plant to the *Rhizobium* decreases due to decreased photosynthetic activity of the legume (Gálvez et al., 2005).

White clover (*Trifolium album* L.) is one of the most drought sensitive components of pastures (Skinner et al., 2004). In pastures, irrigation increases the number of tillers of grasses and the longevity of clover and its dry mass yield, the increment being higher the older the clover pasture. The main reason for the success of clover is increased stolon formation induced by irrigation (García et al., 2010).

Potato is sensitive to water deficit and soil water availability is considered as a major limiting factor in its production and quality (Phene & Sanders, 1976). Water deficit easily leads to significant yield and quality losses. In trials at Potato Research Institute in Finland in 1989-1995 and 1999-2002, irrigation increased tuber yield, starch yield and marketable ware potato yields by 9.1 %, 9.2 % and 22.2 %, respectively (Potato Research Institute, unpublished data). On the other hand, over-irrigation promotes diseases as well as leaching of nutrients and pesticide residues towards groundwater (Pereira & Shock, 2006). In particular, late irrigation at the senescence may increase risks of tuber diseases (Wikman et al., 1996).

Water has a definitive influence on tuber bulking (Wikman et al., 1996). Especially during mid-bulking, three to six weeks after tuber initiation, potato needs an even supply of water (Scherer et al., 1999). Water deficit during tuber bulking usually affects total tuber yield more than quality (King & Stark, 1997).

On average, stored soil and spring moisture supplies are adequate from planting to tuber initiation. Lack of water before tuber initiation reduces tuber set per stem (MacKerron & Jeffries, 1986). Dryness at the tuber initiation phase decreases tuber number (King & Stark, 1997; Scherer et al., 1999). In Finnish conditions, the most decisive phase on tuber formation is about 40 days after planting. Effects on the final tuber yield, however, are seldom clear in these phases (Wikman et al., 1996).

Early season drought is also known to shorten the developmental phases of cereals (Figure 6). In triticale (*Triticosecale*), the phase from emergence to anthesis and to maturity was reduced both in calendar days and in thermal time. The acceleration of development was probably related to a water-deficit induced increase in canopy temperature of 1.3 °C (Estrada-Campuzano et al., 2008). Water deficit results in stomatal closure, and thus decreased gas exchange and transpiration, which decreases the cooling inside leaf cells and leads to increased temperature in leaf tissues. Water deficit affects not only the growth and development of aerial plant parts but also the roots. The seminal roots are shorter and the root volume is lower in cereals, such as barley (Sahnoune et al., 2004), wheat (Guedira et al., 1997), and oat (Larsson & Górny, 1988) when grown under water deficit. In barley, root growth was restricted mostly in deeper (> 30 cm) soil layers (Sahnoune et al., 2004).

Fig. 6. Water deficit hastens the development of cereals. Non-irrigated wheat reached anthesis stage (A, B), whereas irrigated wheat (C, D) was not yet at heading stage on 2 July, 2011.

A common problem in the Boreal region, connected to early season drought, is inhibition of early tillering, which can result in formation of late tillers after rainfall at anthesis (Mäkelä & Muurinen, 2011). These tillers produce spikes which, however, reach maturity several weeks later than the majority of the spikes (Figure 6), causing delays in harvesting, increases in drying costs, and quality losses due to sprouting or immature grains (Kivisaari & Elonen, 1974). According to Kivisaari & Elonen (1974), irrigation of spring barley at an early growth stage (twice 30 mm) significantly decreased moisture content at harvest, number of immature grains and late tiller formation. Even though the number of spikes per plant decreased, single grain weight, number of grains per spike and thus, grain yield, increased significantly. The final increase in grain yield was nearly 70 %.

Fig. 7. Non-irrigated winter wheat cv. Olivin (A) stand includes late-formed tillers, which are still green, whereas the main crop has already reached maturity. Irrigated crop (B) has reached maturity evenly.

Irrigation of spring wheat (35 mm) at the vegetative stage increased the number of spike-bearing tillers and grain yield (Table 1) and decreased the formation of tillers at later growth stages (Figure 7). However, single grain weight, harvest index and number of grains per spike were not significantly different between irrigated and non-irrigated wheat. In the spring, the duration from seeding to anthesis can be lengthened with irrigation by five to seven days (Cutforth et al., 1990), allowing more time for accumulation of vegetative mass and formation of floret structures.

Location Cultivar	Grain yield g m^{-2}	Single grain weight mg	Grains per spike	Spikes per m^2	Harvest index
Location 1, Amaretto					
Irrigated	809	38.4	29	729	0.45
Non-irrigated	406	33.9	27	445	0.42
SEM (df 5)	64.7	2.1	0.7	49.6	0.035
Location 2, Amaretto					
Irrigated	603	41.5	20	738	0.53
Non-irrigated	359	39.5	15	622	0.52
SEM (df 5)	33.5	0.62	1.5	48.5	0.009

Table 1. Grain yield, number of grains per spike, single grain weight, number of spikes per m^2 and harvest index for irrigated and non-irrigated spring wheat cv. Amaretto in 2011 at two different locations (Location 1, Laukka 60 15′ 00′′ N, 23 05′ 00′′ E, alt. 14.0 m and Location 2 Tamminiemi, 60 24′ 00′′ N, 25 40′ 00′′ E, alt. 23.5 m). Plant stands were irrigated (30-35 mm) once at tillering stage.

It also should be pointed out that in coastal areas of Finland, irrigation is sometimes needed to enhance the germination of autumn-sown winter cereals.

4.2 Late season drought and irrigation

Late season drought affects the grain-filling period of both spring and winter cereals. After anthesis, water deficit mainly caused decreases in grain yield and fewer grains in barley (Rajala et al., 2011). At that stage, the limited availability of water and assimilates affects the translocation processes, from sources to sinks, filling grains. In oat, however, water deficit at post-anthesis mainly decreased the number of grains (Peltonen-Sainio & Mäkelä, 1995), similarly to wheat (Rajala et al., 2011), probably due to limited source capacity. Fábián et al. (2011) showed that water deficit occurring after pollination, during early grain development stage, decreases the embryo size and increases the degradation of cell layers surrounding the ovule. It also affects the distribution of starch granules A and B, favouring the A-type. Similarly as for drought occurring early in the season, late season drought also shortens the grain-filling period (Fábián et al. 2011), thus decreasing the grain yield by limiting the length of assimilate transport to grains.

A wet winter may increase the drought vulnerability of winter cereals. As a response to waterlogging, aerenchyma-forming nodal roots located in the top 20 cm develop at the cost of deeper seminal roots. During water deficit in the summer, the nodal roots cannot extract water from the deep soil layers, which multiplies the drought effect and grain yield losses (Dickin & Wright, 2008). In general, root growth is reduced under water deficit, but the reduction is more severe and permanent after anthesis than before terminal spikelet formation. This effect is cumulative at the grain-filling stage, since water uptake rates of roots decrease in relation to crop life (Asseng et al., 1998).

Stem reserves stored prior to anthesis have been considered as an important source of assimilates to maintain grain-filling processes, especially in environments with terminal stress, where the contribution of stem reserves can be as high as 90 % of the final yield (Asseng & Herwaarden, 2003). Foulkes et al. (2007) reported that stem reserves correlated positively with grain yield also in Britain, where rainfall is unpredictable, as it is in the Boreal region.

In spring oilseed rape, water deficit occurring during the seed filling stage had no effect on total dry matter but decreased the number and size of seeds. Stressed plants also had fewer siliquee in comparison with well-watered plants (Jensen et al., 1996). The explanation was offered by Richards & Thurling (1978), who found that in oilseed rape dry weight accumulation before flowering was the major factor affecting seed yield when water deficit occurred after flowering, whereas in turnip rape dry weight accumulation after flowering was more important. However, Tesfamariam et al. (2010) found that water deficit during the seed-filling period hastened maturity over 100 growing degree days. Flower dropping caused by water deficit limits the grain yield in grain legumes. It decreases the number of sinks and may cause feedback inhibition of photosynthesis. On the other hand, poor carbohydrate translocation to the reproductive sinks may limit both seed size and number (Tesfaye et al., 2006).

Water deficit limits sugar beet root and sugar yield and quality throughout Europe (Hoffman et al., 2009), even though it has been commonly considered to be a drought tolerant crop (Vamerali et al., 2009). Water deficit decreases the processing quality of roots since the potassium and α-amino nitrogen concentrations increase due to osmotic adjustment and nitrogen metabolism (Bloch & Hoffmann, 2005). It also affects the decay of sugar beet fibrous roots, which form a dense and deep system, even though their fraction of biomass is 3 - 10 % of the total biomass (Brown et al., 1987). Under water deficit the longevity of fibrous roots increases. Life span of roots is longest at a depth where there is least water available. This decreases the cost of carbon for renewal of roots (Vamerali et al., 2009).

In sugar beet, water deficit decreased the leaf lifespan by 20 days and net photosynthesis of leaves. Moreover, the photosynthesis of mature leaves could not fully recover from water deficit (Monti et al., 2007), decreasing the ability of the crop to capture solar energy, and thus leading to decreased root and sugar yield. According to Ober et al. (2005) the sugar beet ideotype for environments with limited water availability should be able to maintain a green and succulent canopy late into the season and thus have low leaf senescence and specific leaf weight as well as high transpiration rate and ability to use water from deep soil layers. That will ensure good resource capture ability of the crop and good yield. For sugar beet, late season irrigation induces formation of deep roots (>1 m) and reduction of penetration resistance in deep soil due to irrigation may further induce root growth (Vamerali et al, 2009). Camposeo & Rubino (2003) stated that low interval drip irrigation of sugar beet can increase the root:shoot ratio by 35 % and thus result in yield increases. In Sweden, irrigation throughout the growing season increased the root yield almost 14 t/ha and sugar yield by 2.6 t/ha. Late season irrigation increased root yield by 9.6 t/ha and sugar yield by 1.8 t/ha. Irrigation did not affect markedly the root quality (Persson, 1993). In Finland, late season irrigation increased root yield by 18 t/ha and sugar yield over 2.5 t/ha (Erjala, 2002).

5. Effect of frost on crop development, growth and yield

Spring and autumn frost can occur every now and then in the Boreal region, causing yield losses. To avoid this, farmers have to delay sowing spring crops and use early maturing cultivars. Thus, the growing season is limited and leads to indirect yield losses. Frosts can damage spring crops in particular. Frost damage occurs in the spring most typically, but sometimes also in the autumn. This can be explained by the farmers' experience and knowledge-based selection of cultivars with adequate growing time.

5.1 Spring frosts

The early vegetative stage of spring crops is vulnerable to frosts (Andrews, 1987). Most severe damage caused by spring frosts occurs usually in sugar beet and oilseed brassica crops, when the entire canopy can be killed (Figure 9). In these species the apical bud is located over the insulating soil surface and is thus sensitive to damage. In cereals such as oat, wheat, barley and maize, the apical bud is located below the insulating soil surface and is not easily damaged. Frost damage mainly slows down biomass accumulation of cereals due to decreased photosynthesis following membrane leakage and reduced mesophyll conductance, decreased photosynthetic leaf area, and thus causes yield decrease (Andrews, 1987). According to Gusta & O'Connor (1987), frost also slows down the development rate of oilseed rape and mustard (*Sinapis alba* L.) by approximately nine days and spring cereals by up to ten days. On the other hand, McKenzie et al. (1982) reported a reduction in number of days to heading in barley after frost damage and concluded that it was due to response to prevailing photoperiod, temperature and soil moisture.

Fig. 9. Spring frost damage in A) sugar beet and B) barley. Some of the sugar beet plantlets have been completely destroyed by frost. The apical bud of sugar beet is the uppermost part of the plant and thus sensitive to damage. Barley survives the frost even though the leaves are damaged because the apical bud is sheltered below the soil surface during the vegetative stage.

Gusta & O'Connor (1987) found that there were no cultivar differences in frost tolerance for mustard and oilseed rape, but the developmental stage did affect the tolerance. Plantlets having 4 – 6 leaves were 1 – 2 °C more frost tolerant than plantlets at the cotyledon stage. Frost tolerance of turnip rape is significantly improved already after a two-day hardening in the field, in terms of death of unhardened plantlets after a night frost and survival without damage of hardened plantlets (K. Pahkala, personal communication). However, hardening resulted in reduced plant height and leaf area. The cultivar differences in growth response to hardening as well as in frost (-5 °C) tolerance were significant. During hardening the hexadecatrienoic acid (16:3) concentration of leaves increased, whereas there was no change in α-linolenic acid (18:3) concentration (Pahkala et al., 1991).

Among spring cereal species at the two-leaf stage, oat is most frost sensitive and wheat most frost tolerant (Gusta & O'Connor, 1987). However, at anthesis, barley is most frost tolerant, probably as it is pollinated in the boot (Passioura & Angus, 2010). McKenzie et al. (1982) found significant differences among spring barley cultivars in frost tolerance when plants were subjected to -5.6 °C at the two-leaf stage. In wheat, spring frost at the two-leaf stage increased the number of spikes and delayed maturity for one to ten days. The delay in maturity was less obvious in barley and wheat. Frost treatment increased wheat yield but tended to decrease the barley and oat yield (Gusta & O'Connor, 1987). In Finland, barley has been considered to be more frost tolerant than wheat and usually frost has induced formation of spike-bearing tillers in barley. According to McKenzie et al. (1982), it seems that early maturing cultivars are more sensitive to frost than late maturing cultivars. Cool-season grain legumes are tolerant to frost at the vegetative stage, but pollen and flower structures are sensitive to low temperatures (Stoddard et al., 2006; Link et al., 2010; F. L. Stoddard, personal communication).

In the Boreal region, winter rye can sometimes be damaged by spring frost at the time of pollination, causing incomplete fertilization of florets and leading to reduced grain yield. A low temperature of -4 °C caused disruption of membrane structures in wheat spikes at the heading stage (Marcellos & Single, 1984). That resulted in destruction of entire spikes on some occasions when temperature decreased 1 °C below a cultivar-dependent threshold temperature. On the other occasions, the spike consisted of both fertile and sterile spikelets. The occurrence of sterile spikelets did not depend on their position within the spike, whereas the higher order florets within the spikelet remained fertile in many cases

(Marcellos & Single, 1984). Marcellos & Single (1984) explained this phenomenon by discontinuous extension of ice nucleation within the spike. An ice front can move from a single nucleating point on a leaf at approximately 120 cm/min, but it is delayed by nodes in the stem, rachis and spikelets (Andrews, 1987). However, in wheat, cold stress similarly to drought, induces irreversible damage in pollen development at the young microspore stage and thus formation of infertile pollen grains (Ji et al., 2011). This damage is probably similar to that in pollen development in rye.

5.2 Autumn frosts

Autumn frosts can occur during the grain filling stage of cereals. The risk increases with the late maturing cultivars. Frost affects the biological processes of grain filling and thus the grain weight remains low, the grain is of poor quality and in some cases only empty hulls remain. Occurrence of frost has resulted in formation of shrivelled and shrunken wheat grains and in less severe cases blistering of the grain surface and thus, low grain weight during the grain filling stage (Cromey et al., 1998). Cromey et al. (1998) suggested that the damage was due to death of outer tissues of grains, most damage occurring in the testa and pericarp and to some extent in the endosperm. The pericarp and testa were crushed and the dead cells were in a loose arrangement in frosted grains. Starch accumulation was reduced severely, probably since the number of living endosperm cells able to take up carbohydrates was decreased. However, the surviving tissues could compensate to some degree for the damage. Cromey et al. (1998) concluded that the original aleurone layer could have been reformed from the outermost endosperm cells, and therefore the germination ability of the grains was maintained. When frost occurred at the early dough stage, the germination of wheat decreased from 98 % to 62 % and barley from 82 % to 40 %, and oat completely failed to germinate, but at late dough stage the germination was not affected in any of the species studied (Gusta & O'Connor, 1987). However, at the grain filling stage wheat seems to be the most frost tolerant cereal species in general (Gusta & O'Connor, 1987). In brassicas, the seed yield, and especially the oil quality, is most affected by frost (Gusta & O'Connor, 1987). Pahkala et al. (1991) reported a decrease in α-linolenic acid and an increase in oleic acid concentration in ripening seeds of turnip rape after frost. Cool-season grain legumes are tolerant to frost at later stages of pod filling (Stoddard et al., 2006; Link et al., 2010; F. L. Stoddard, personal communication).

Frost also severely affects the baking quality of the grains and in many cases results in rejection of the yield by the milling industry. Dexter et al. (1985) reported decreased visual quality, grain weight and flour yield and increased ash content and grain hardness of frosted wheat grains. Falling number was only slightly lower in frosted grain in comparison with unfrosted grains. Flour was darker the more severe the frost damage and protein content of the grains was similar to that of unfrosted grains. The increased hardness and maltose content of grains, as well as loss of gluten functionality, resulted in increased flour starch damage. However, no sprout damage was observed, even though the falling number decreased and maltose content increased (Dexter et al., 1985). The estimate of yield loss in small-grain cereals caused by autumn frost varied from 13 to 33 %, although it could have been even more due to loss of shrivelled grain during harvest (Cromey et al., 1998).

5.3 Frost protection

Irrigation is successfully used to prevent damage due to night frost. In direct protection, the temperature of the plant is kept above the freezing point by using latent heat fusion of water. The crop is irrigated for the whole time that temperature is at or below zero, forming a film of ice on the plant which releases energy, preventing the tissue from freezing. Irrigation is started when temperature decreases to +1–0 °C, and it is stopped when the ice on the plant starts to melt (van der Gulik & Williams, 1988; Ingvarsson, 1992; Svensson, 2003). In this way, irrigation can protect the crop until -7 – -8 °C (Ingvarsson, 1992).

In the indirect method, the soil is irrigated on the morning of the day when frost is anticipated. Wet soil traps plenty of warmth during a day and releases it during the night, preventing frost damage up to -2 – - 3 °C. The shelter effect is highest about 30 cm above the soil surface, so indirect frost protection is suitable only for low growing crops (Ingvarsson, 1992).

Irrigation as a direct protection against freezing temperature is mostly used in the production of berries and fruits where inputs are high (van der Gulik & Williams, 1988). In Boreal region, especially in Nordic countries, first-early potatoes are so valuable that irrigation generally is used to prevent frost damage (Wikman et al., 1996).

6. Future challenges

Alcamo et al. (2000) suggested that industrial and economic growth in regions under severe water stress (high water withdrawal compared with water availability) may be limited in the near future. Climate change may decrease water availability and thus increase water stress in those areas in the longer term. This means that agriculture will have to compete harder with domestic and industrial water use. The Boreal region will, however, remain a region without water stress in the longer term (Alcamo et al., 2000).

Climate change will probably increase the frequency of drought spells also in the European Boreal region (Olesen et al., 2011). The changes are expected to be, however, smaller than in the southern parts of Europe. The increase in drought frequency would increase the need for irrigation also in northern areas. The risk of late spring frosts and early autumn frosts is likely to decrease due to climate change (Olesen et al., 2011). There is still an avenue for plant breeding in improving frost tolerance at the grain filling stage in cereals since genetic variation for the trait is known to exist (Marcellos & Single, 1984), as well as at early growth stages. In dry areas, especially in a Mediterranean climate, selection of drought tolerant crop species and cultivars has been considered to be one of the most important means of alleviating agricultural problems (Ashraf et al., 1992). Drought has not commonly been considered a serious problem in the Boreal region. However, in the future, more attention should be paid to methods and technologies for alleviating short-term drought problems.

7. References

Anonymous, 2007. Vattenuttag och vattenanvändning i Sverige 2005. *Statistics Sweden* 2007. Available from http://www.scb.se/Pages/PublishingCalendarViewInfo_259923.aspx?PublObjId=6598

Alcamo, J.; Henrichs, T. & Rösch, T. (2000). World water in 2025. Kassel World Water Series, Report No 2. Available from http://www.usf.uni-kassel.de/ftp/dokumente/kwws/kwws.2.pdf

Andrews, C.J. (1987). Low-temperature stress in field and forage crop production – an overview. *Canadian Journal of Plant Science*, 67, 1121-1133, ISSN 0008-4220

Ashraf, M.; Bokhari, H. & Cristiti, S.N. (1992). Variation in osmotic adjustment of lentil (*Lens culinaris* Medic) in response to drought. *Acta Botanica Neerlandica*, 41, 51-62, ISSN 0044-5983

Asseng, S.; Ritchie, J.T.; Smucker, A.J.M. & Robertson, M.J. (1998). Root growth and water uptake during water deficit and recovering in wheat. *Plant and Soil*, 201, 265-273, ISSN 0032-079X

Asseng, S. & van Herwaarden, A.F. (2003). Analysis of the benefits to wheat yield from assimilates stored prior to grain filling in a range of environments. *Plant and Soil*, 256, 217-229, ISSN 0032-079X

ATLAS. (2007). The Atlas of Canada. Available from http://atlas.nrcan.gc.ca

Bloch, D. & Hoffmann, C. (2005). Seasonal development of genotypic differences in sugar beet (*Beta vulgaris* L.) and their interaction with water supply. *Journal of Agronomy and Crop Science*, 191, 263-272, ISSN 0931-2250

Boyer, J.S. (1982). Plant productivity and environment. *Science*, 218, 443-448, ISSN 0036-8075

Briggs, K.G.; Kiplagat, O.K. & Johnson-Flanagan, A.M. (1999). Effects of pre-anthesis moisture stress on floret sterility in some semi-dwarf conventional and conventional height spring wheat cultivars. *Canadian Journal of Plant Science*, 79, 515-520, ISSN 0008-4220

Broughton, B.S. (1995). Economic, production and environmental impacts of subirrigation and controlled drainage, In: *Subirrigation and drainage*, H.W. Belcher & F.M. D'Itri, (Eds.), 183.191, CRC Press, ISBN 1-56670-139-2, Boca Raton, Florida, USA.

Brown, D.M. & Blackburn, W.J. (1987). Impacts of freezing temperatures on crop production in Canada. *Canadian Journal of Plant Science*, 67, 1167-1180, ISSN 0008-4220

Brundell, P.; Kanlen, F. & Westöö, A-K. (2008). *WaterUuse for Irrigation*. Report on Grant Agreement No 71301.2006.002-2006.470. Statistiska Centralbyrån, Statistics Sweden. Available from http://circa.europa.eu/Public/irc/dsis/envirmeet/library?l=/meetings_2008_archive/statistics_09-101008/background_documents/sweden_irrigationpdf/_EN_1.0_&a=d

Brouwer, C.; Prins, K.; Kay, M. & Heibloem, K. (1988). *Irrigation Water Management: Irrigation Methods*. Training manual No. 5. Available from http://www.fao.org/docrep/S8684E/S8684E00.htm

Brown, K.F.; Messem, A.B.; Dunham, R.J. & Biscoe, P.V. (1987). Effect of drought on growth and water use of sugar beet. *Journal of Agricultural Science*, 109, 421-435, ISSN 0021-8596

Camposeo, S. & Rubino, P. (2003). Effect of irrigation frequency on root water uptake in sugar beet. *Plant and Soil*, 253, 301-309, ISSN 0032-079X

Cromey, M.G.; Wright, D.S.C. & Boddington, H.J. (1998). Effects of frost during grain filling of wheat yield and grain structure. *New Zealand Journal of Crop and Horticultural Science*, 26, 279-290, ISSN 0114-0671

Cutforth, H.W.; Campbell, C.A.; Brandt, S.A.; Hunter, J.; Judiesch, D.; DePauw, R.M. & Clarke, J.M. (1990). Development and yield of Canadian western red spring and Canada prairie spring wheats as affected by delayed seeding in the brown and dark brown soil zones of Saskatchewan. *Canadian Journal of Plant Science*, 70, 639-660, ISSN 0008-4220

Dexter, J.E.; Martin, D.G.; Preston, K.R.; Tipples, K.H. & MacGregor, A.W. (1985). The effect of frost damage on the milling and baking quality of red spring wheat. *Cereal Chemistry*, 62, 75-80, ISSN 0009-0352

Dickin, E. & Wright, D. (2008). The effects of winter waterlogging and summer drought on the growth and yield of winter wheat (*Triticum aestivum* L.). *European Journal of Agronomy* 28, 234-244, ISSN 1161-0301

Drury, C. F., Tan, C. S., Gaynor, J. D., Oloya, T. O. & Welacky, T. W. (1996). Influence of controlled drainage-subirrigation on surface and tile drainage nitrate loss. *Journal of Environmental Quality*, 25, 317-324, ISSN 0047-2425

Dumler, T.J.; O'Brien, D.M. & Rogers, D.H. (2007). Irrigation Capital Requirements and Energy Costs, 24.8.2011, Available from
http://www.ksre.ksu.edu/library/agec2/mf836.pdf

Erjala, M. (2002). Kastelukokeen tulokset. *Juurikassarka*, 1, 16-17, ISSN 0789-2667

Estrada-Campuzano, G.; Miralles, D.J. & Slafer, G.A. (2008). Genotypic variability and response to water stress of pre- and post-anthesis phases in triticale. *European Journal of Agronomy*, 28, 171-177, ISSN 1161-0301

Fábián, A.; Jäger, K.; Rakszegi, M. & Barnabás, B. (2011). Embryo and endosperm development in wheat (*Triticum aestivum* L.) kernels subjected to drought stress. *Plant Cell Reports*, 30, 551-563, ISSN 0721-7714

Forsman, K. (2006). Perunan kastelumenetelmät vertailussa. *Tuottava Peruna*, 33, 16-17, ISSN 0787-670X

Foulkes, M.J.; Sylvester-Bradley, R.; Weightman, R. & Snape, J.W. (2007). Identifying physiological resistance in winter wheat. *Field Crops Research*, 103, 11-24, ISSN 0378-4290

Geohring, L.D; van Es, H.M. & Buscaglia, H.J. (1995). Soil water and forage response to controlled drainage, In: *Subirrigation and drainage,* H.W. Belcher & F.M. D'Itri, (Eds.), 183-191, CRC Press, ISBN 1-56670-139-2, Boca Raton, Florida, USA

Gilliam, J.W & Skaggs, R.W. (1986). Controlled agricultural drainage to maintain water quality. *ASCE Journal of Irrigation and Drainage Engineering*, 112, 254-263, ISSN 0733-9437

Gálvez, L.; González, E.M. & Arrese-Igor, C. (2005). Evidence for carbon flux shortage and strong carbon/nitrogen interactions in pea nodules at early stages of water stress. *Journal of Experimental Botany* 56, 2551-2561, ISSN 0022-0957

García, J.A.; Piñeiro, G.; Arana, S. & Santiñaque, F.H. (2010). Moisture deficit and defoliation effects on white clover yield and demography. *Crop Science*, 50, 2009-2020, ISSN 0011-183X

Guedira, M.; Shroyer, J.P; Kirkham, M.B. & Paulsen, G.M. (1997). Wheat coleoptiles and root growth and seedling survival after dehydration and rehydration. *Agronomy Journal*, 89, 822-826, ISSN 0002-1962

van der Gulik, T.W. & Williams, R.J. (1988). *B.C. Frost Protection Guide*, Irrigation Industry Association of British Columbia, ISBN 0-7726-0705-2, Vernon, B.C., Canada

Gusta, L.V. & O'Connor, B.J. (1987). Frost tolerance of wheat, oats, barley, canola and mustard and the role of ice-nucleating bacteria. *Canadian Journal of Plant Science*, 67, 1155-1165, ISSN 0008-4220

Hooli, J. (1971). Säätekijöiden vaikutuksesta viljelykasvien satoihin ja vesitalouteen. English summary: Effect of weather on water economy and crop yields. *Tieteellisiä julkaisuja*, Helsingin teknillinen korkeakoulu, No. 35. 244 p. ISSN 0355-774X

Hoffmann, C.M; Huijbregts, T.; van Swaaij, N. & Jansen, R. (2009). Impact of different environments in Europe on yield and quality of sugar beet genotypes. *European Journal of Agronomy*, 30, 17-26, ISSN 1161-0301

Holzapfel, E.A.; Pannunzio, A.; Lorite, I.; Silva de Oliveira, A.S. & Farkas, I. (2009). Design and management of irrigation systems. Review. *Chilean Journal of Agricultural Research*, 69, 17-25 ISSN 0718-5820

Hämet-Ahti, L. (1981). The boreal zone and its biotic subdivision. *Fennia*, 159, 69-75, ISSN 0015-0010

Ilmatieteenlaitos. (2011). Suomen nykyilmastoa kuvaavat lämpötilan, sateen ja lumensyvyyden keskiarvot. Available from http://ilmatieteenlaitos.fi/pitkan-ajan-tilastot

Ingvarsson, A. (1992). Bevattning. Ekologisk trädgårdsodling. Från teori till praktik. Jordbruksverket (SJV). Available from http://www.vaxteko.nu/html/sll/sjv/utan_serietitel_sjv/UST92-3/UST92-3N.HTM

Jamieson, P.D.; Martin, R.J.; Francis, G.S. & Wilson, D.R. (1995). Drought effects on biomass production and radiation-use efficiency in barley. *Field Crops Research*, 43, 77-86, ISSN 0378-4290

Jensen, C.R.; Mogensen, V.O.; Mortensen, G.; Fieldsend, J.K.; Milford, G.F.J.; Andersen, M.N. & Thage, J.H. (1996). Seed glucosinolate, oil, and protein contents of field-grown rape (*Brassica napus* L.) affected by soil drying and evaporative demand. *Field Crops Research*, 47, 93-105, ISSN 0378-4290

Ji, X.; Shiran, B.; Wan, J.; Lewis, D.C.; Jenkins, C.L.D.; Condon, A.G.; Richards, R.A. & Dolferus, R. (2010). Importance of pre-anthesis anther sink strength for maintenance of grain number during reproductive stage water stress in wheat. *Plant, Cell and Environment* 33, 926-942, ISSN 0140-7791

Ji, X.; Dong, B.; Shiran, B.; Talbot, M.J.; Edlington, J.E.; Hughes, T.; White, R.G.; Gubler, F. & Dolferus, R. (2011). Control of ABA catabolism and ABA homeostasis is important for reproductive stage stress tolerance in cereals. *Plant Physiology*, 156, 647-662, ISSN 0032-0889

Jordbruksverket. (2011). Available from http://www.sjv.se

Järvinen, J. (2007). Haihdunta. In: *Hydrologinen vuosikirja 2001-2005, Suomen ympäristö,* No. 44, J. Korhonen (Ed.), pp. 169-175. ISBN 978-952-11-2930-8

Khan, H.R.; Paull, J.G.; Siddique, K.H.M. & Stoddard, F.L. (2010). Faba bean breeding for drought-affected environments: A physiological and agronomic perspective. *Field Crops Research*, 115, 279-286, ISSN 0378-4290

King, B.A. & Stark, J.C. (1997). Potato Irrigation Management. University of Idaho, Cooperative Extension System, Bulletin 789, Available from http://www.cols.uidaho.edu/edcomm/pdf/BUL/BUL0789.pdf

Kivisaari, S. & Elonen, P. (1974). Irrigation as a method preventing detrimental late tillering of barley. *Journal of the Scientific Agricultural Society in Finland* 46, 194-207, ISSN 0024-8835

Kuusisto, E. (2010). Väärinymmärretty lumi, 14.12.2010, Available from http://www.ymparisto.fi/default.asp?contentid=68383

Lalonde S.; Beebe, D.U. & Saini, H.S. (1997). Early signs of disruption of wheat anther development associated with the induction of male sterility by meiotic-stage water deficit. *Sexual Plant Reproduction*, 10, 40-48, ISSN 0934-0882

Larsson, S. & Górny, A.G. (1988). Grain yield and drought resistance indices in oat cultivars in field rain shelter and laboratory experiments. *Journal of Agronomy and Crop Science*, 161, 227-286, ISSN 0931-2250

Link, W.; Balko, C. & Stoddard, F.L. (2010). Winter hardiness in faba bean: Physiology and breeding. *Field Crops Research*, 115, 287-286, ISSN 0378-4290

Madramootoo, C.A.; Helwig, T.G. & Dodds, G.T. (2001). Managing water tables to improve drainage water quality in Quebec, Canada. *Transactions of the ASAE*, 44, 1511-1519, ISSN 0001-2351

Marcellos, H. & Single, W.V. (1984). Frost injury in wheat ears after emergence. *Australian Journal of Plant Physiology*, 11, 7-15, ISSN 1445-4408

MacKerron, D.K.L. & Jefferies, R.A. (1986). The influence of early soil moisture stress on tuber numbers in potato. *Potato Research*, 29, 349-359, ISSN 0014-3065

McKenzie, J.S.; Faris, D.G. & De Pauw, R.M. (1982). Influence of simulated spring frost on growth and yield of three barley cultivars. *Canadian Journal of Plant Science*, 62, 81-88, ISSN 0008-4220

Mela, T.N.J. (1996). Northern agriculture: constraints and responses to global climate change. *Agricultural and Food Science in Finland*, 5, 229-234, ISSN 1459-6067

Melvin, S.W. & Kanvar, R.S. (1995). Environmental and economic impacts of a recycling subirrigation-drainage system. , In: *Subirrigation and drainage,* H.W. Belcher & F.M. D'Itri, (Eds.), 183-191, CRC Press, ISBN 1-56670-139-2, Boca Raton, Florida, USA

Mogensen, V.O.; Jensen, C.R.; Mortensen, G.; Thage, J.H.; Koribidis, J. & Ahmed, A. (1996). Spectral reflectance index as an indicator of drought of field grown oilseed rape (*Brassica napus* L.). *European Journal of Agronomy*, 5, 125-135, ISSN 1161-0301

Monti, A; Barbanti, L. & Venturi, G. (2007). Photosynthesis on individual leaves of sugar beet (*Beta vulgaris*) during the ontogeny at variable water regimes. *Annals of Applied Biology*, 151, 155-165, ISSN 0003-4746

Muellera, L.; Behrendtb A.; Schalitzb, G. & Schindler, U. (2005). Above ground biomass and water use efficiency of crops at shallow water tables in a temperate climate. *Agricultural Water Management*, 75, 117-136, ISSN 0378-3774

Mukula, J. & Rantanen, O. (1987). Climatic risks to the yield and quality of field crops in Finland. I. Basic facts about Finnish field crops production. *Annales Agriculturae Fenniae*, 26, 1-18, ISSN 1459-6067

Mäkelä, P. & Muurinen, S. (2011). Uniculm and conventional tillering barley accessions under northern growing conditions. *Journal of Agricultural Science*, in press, ISSN 0021-8596

Mäkelä, P.; Muurinen, S. & Peltonen-Sainio, P. (2008). Spring cereals: from dynamic ideotypes to cultivars in northern latitudes. *Agricultural and Food Science*, 17, 289-306, ISSN 1459-6067

Olesen, J.E. & Bindi, M. (2002). Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy*, 16, 239-262, ISSN 1161-0301

Olesen, J.E.; Jørgensen, L.N. & Mortensen, J.V. (2000). Irrigation strategy, nitrogen application and fungicide control in winter wheat on a sandy soil. II. Radiation interception and conversion. *Journal of Agricultural Science*, 134, 13-23, ISSN 0021-8596

Olesen, J.E.; Trnka, M.; Kersebaum, K.C.; Skjelvåg, K.; Seguin, B.; Peltonen-Sainio, P.; Rossi, F.; Kozyra, P. & Micale, F. (2011). Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy*, 34, 96-112, ISSN 1161-0301

Ober, E.S.; Le Bloa, M. ; Clark, C.J.A. ; Royal, A. ; Jaggard, K.W. & Pidgeon, J.D. (2005). Evaluation of physiological traits as indirect selection criteria for drought tolerance in sugar beet. *Field Crops Research*, 91, 231-249, ISSN 0378-4290

Pahkala, K.; Laakso, I. & Hovinen, S. (1991). The effect of frost treatment on turnip rape seedlings, ripening seeds and their fatty acid composition, *Proceedings of GCIRC Eight International Rapeseed Congress*, D.I. McGregor, (Ed.), pp. 1749-1753, Saskatoon, Saskatchewan, Canada, July 9 -11, 1991

Pajula, H. & Triipponen, J-P. (2003). Selvitys Suomen kastelutilanteesta, esimerkkialueena Varsinais-Suomi. *Suomen ympäristö*, No. 629. ISBN 952-11-1416-9

Passioura, J.B. & Angus, J.F. (2010). Improving Productivity of Crops in Water-Limited Environments, In: *Advances in Agronomy*, D.L. Sparks, (Ed.), Vol. 106, pp. 37-75, Academic Press, ISBN 978-0-12-381035-9, Burlington, MA, USA

Peltonen-Sainio, P.; Jauhiainen, L. & Hakala, K. (2011). Crop responses to temperature and precipitation according to long-term multi-location trails at high-latitude conditions. *Journal of Agricultural Science* 149, 49-62, ISSN 0021-8596

Peltonen-Sainio, P. & Mäkelä, P. (1995). Comparison of physiological methods to assess drought tolerance in oats. *Acta Agriculturae Scandinavica, Section B – Plant Soil Science*, 45, 32-38, ISSN 0906-4710

Pereira, A.B. & Shock, C.C. (2006). Development of irrigation best management practices for potato from a research perspective in the United States. *Sakia.org e-publish*, 1, 1-20

Perlman, H. (2011). The Water Cycle: Sublimation. Available from http://ga.water.usgs.gov/edu/watercyclesublimation.html)

Persson, R. (1993). Bevattningstidpunkter i sockerbetor. Available from http://www.vaxteko.nu/html/sll/slu/meddelande_sjfd/MSJ40/MSJ40W.HTM

Phene, C.J. & Sanders, D.C. (1976). High-frequency trickle irrigation and row spacing effects on yield and quality of potatoes. *Agronomy Journal*, 68, 602-607, ISSN 0002-1962

Playán, E. & Mateos, L. (2006). Modernization and optimization of irrigation systems to increase water productivity. *Agricultural Water Management*, 80, 100-116, ISSN 0378-3774

Puustinen, M.; Merilä, E.; Palko, J.& Seuna, P. (1994). Kuivatustila, viljelykäytäntö ja vesistökuormitukseen vaikuttavat ominaisuudet Suomen pelloilla. *Vesi- ja ympäristöhallinnon julkaisuja - sarja A*. ISBN 951-47-9883-X, ISSN 0786-9592.

Rajala, A.; Hakala, K.; Mäkelä, P.; Muurinen, S. & Peltonen-Sainio, P. (2009). Spring wheat response to timing of water deficit through sink and grain filling capacity. *Field Crops Research*, 114, 263-271, ISSN 0378-4290

Rajala, A.; Hakala, K.; Mäkelä, P. & Peltonen-Sainio, P. (2011). Drought effect on grain number and grain weight at spike and spikelet level in six-row spring barley. *Journal of Agronomy and Crop Science*, 197, 103-112, ISSN 0931-2250

Richards, R.A. & Thurling, N. (1978). Variation between and within species of rapeseed (Brassica campestris and B. napus) in response to drought stress. II. growth and development under natural drought stresses. *Australian Journal of Agricultural Research*, 29, 479-490, ISSN 0004-9409

Sahnoune, M.; Adda, A.; Soualem, S.; Harch, M.K. & Merah, O. (2004). Early water-deficit effects on seminal roots morphology in barley. *Comptes Rendus Biologies*, 327, 389-398, ISSN 1631-0691

Saini, H.S. & Aspinall, D. (1981). Effect of water deficit on sporogenesis in wheat (*Triticum aestivum* L.). *Annals of Botany*, 48, 623-633, ISSN 0305-7364

Saini, H.S. & Westgate, M.E. (2000). Reproductive Development in Grain Crops During Drought, In: *Advances in Agronomy*, D.L. Sparks, (Ed.), Vol. 68, pp. 59-96, Academic Press, ISBN 978-0-12-00768-4, Burlington, MA, USA

Sammis, T.W. (1980). Comparison of sprinkler, trickle, subsurface and furrow irrigation methods for row crops. *Agronomy Journal*, 72, 701-704, ISSN 0002-1962

Scherer, T.F.; Franzen, D.; Lorenzen, J.; Lamey, A.; Aakre, D. & Preston, D.A. (1999). Growing Irrigated Potatoes. AE-1040 Available from http://www.ag.ndsu.edu/pubs/plantsci/rowcrops/ae1040w.htm

Serraj, R.; Sinclair, T.R. & Purcell, L.C. (1999). Symbiotic N2 fixation response to drought. *Journal of Experimental Botany* 50, 143-155, ISSN 0022-0957

Shock, C. (2006). Drip Irrigation: An Introduction. Sustainable Agriculture Techniques EM 8782-E. Available from http://www.extension.oregonstate.edu/catalog/pdf/em/em8782-e.pdf)

Skinner, R.H.; Gustine, D.L. & Sanderson, M.A. (2004). Growth, water relations, and nutritive value of pasture species mixtures under moisture stress. *Crop Science*, 44, 1361-1369, ISSN 0011-183X

Solantie, R. (1980). Kesän yölämpötilojen ja hallojen alueellisuudesta Suomessa. *Maataloushallituksen Aikakauskirja*, 4, 18-24, ISSN 0355-0486

STATCAN. (2009). Statistics Canada. Available from http://www.statcan.gc.ca/pub/16-001-m/2009008/userdef-defusager1-eng.htm

Stoddard, F.L.; Balko, C.; Erskine, W.; Khan, H.R.; Link, W. & Sarker, A. (2006). Screening techniques and sources of resistance to abiotic stresses in cool-season food legumes. *Euphytica* 147, 167-186, ISSN 0014-2336

Svensson, S.-E. (2003). Bevattning i grönsaksodling. Ekologisk odling av grönsaker på friland. Jordbruksverket 2003. Available from http://www2.sjv.se/webdav/files/SJV/trycksaker/Pdf_ovrigt/p7_12.pdf

Tesfamariam, E.H; Annandale, J.G & Steyn, J.M. (2010). Water stress effects on winter canola growth and yield. *Agronomy Journal*, 102, 658-666, ISSN 0002-1962

Tesfaye, K.; Walker, S. & Tsubo, M. (2006). Radiation interception and radiation use efficiency of three grain legumes under water deficit conditions in a semi-arid environment. *European Journal of Agronomy*, 25, 60-70, ISSN 1161-0301

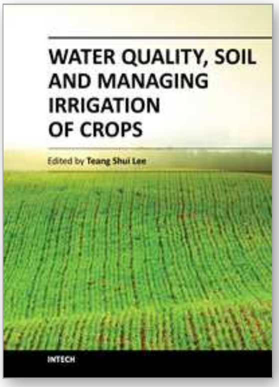
TIKE. (2010). Maataloustilastot. Available from http://www.maataloustilastot.fi

Vamerali, T.; Guarise, M.; Ganis, A. & Mosca, G. (2009). Effects of water and nitrogen management on fibrous root distribution and turnover in sugar beet. *European Journal of Agronomy*, 31, 69-76, ISSN 1161-0301

Wallen, C. C. (1966). Global solar radiation and potential evapotranspiration in Sweden. *Tellus*, 18, 786-800, ISSN 2153-3490

Wiklund, A. & Ekelöf, J. (2006). Droppbevattningens inverkan på kvalitet och kvantitet hos *Solanum tuberosum* L, i jämförelse med konventionell spridarbevattning. Bachelor (Kandidatuppsats) inom Hortonomprogrammet DSH. SLU Alnarp, Institution för landskaps- och trädgårdsteknik. *Rapport*, 3, 1-33, ISSN 1652-1552

Wikman, U.; Torttila, A.; Virtanen, A. & Kuisma, P. (1996) Perunan Vesitalous ja Sadetus. *Perunantutkimuslaitoksen julkaisu* 3, 1-31, ISSN 0787-7323



Water Quality, Soil and Managing Irrigation of Crops
Edited by Dr. Teang Shui Lee

ISBN 978-953-51-0426-1
Hard cover, 242 pages
Publisher InTech

Published in print edition March, 2012

The book entitled Water Quality, Soil and Managing Irrigation of Crops comprises three sections, specifically: Reuse Water Quality, Soil and Pollution which comprises five technical chapters, Managing Irrigation of Crops with four, and Examples of Irrigation Systems three technical chapters, all presented by the respective authors in their own fields of expertise. This text should be of interest to those who are interested in the safe reuse of water for irrigation purposes in terms of effluent quality and quality of urban drainage basins, as well as to those who are involved with research into the problems of soils in relation to pollution and health, infiltration and effects of irrigation and managing irrigation systems including basin type of irrigation, as well as the subsurface method of irrigation. The many examples are indeed a semblance of real world irrigation practices of general interest to practitioners, more so when the venues of these projects illustrated cover a fair range of climate environments.

Pirjo Mäkelä, Jouko Kleemola and Paavo Kuisma (2012). Irrigation of Field Crops in the Boreal Region, Water Quality, Soil and Managing Irrigation of Crops, Dr. Teang Shui Lee (Ed.), ISBN: 978-953-51-0426-1, InTech, Available from: http://www.intechopen.com/books/water-quality-soil-and-managing-irrigation-of-crops/irrigation-of-field-crops-in-the-boreal-region

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821