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Water stress assessment for a better within-field Nitrogen and irrigation management

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Abstract.

Swedish crops production is predominantly rainfed; and until now, food security has been safeguarded by relying on imports if seasonal variations of rainfall reduce yield quantity and quality. In Sweden, based on climate change scenarios, farmers' organizations and representatives consider water to be a critical factor that potentially will limit the yield levels to a larger extent in the future. In rainfed cultivation, the soil type and topography affect the soil water status within a field, which in turn affects the nutrients availability for the plant especially in dry years. The variation in the water status is a key issue to an efficient spatiotemporal application of various inputs (e.g. fertilizers and irrigation), it is also crucial for the potential reduction of negative environmental impact of excessive nutrients rates. In this study, the correlation between crop water status and N uptake is assessed at the within field scale, under different scenarios of N rate and irrigation, to better understand the correlation between water status and N uptake and how it can vary within a field. The study was carried out for two cropping seasons (2020-2021) in Spring Oates (Galant, SW 051020) at the SLU's research station in south western Sweden representing intense cereal production area. The field trials was designed at small plots (3×3m), at five different places within the field. Soil humidity, weather, leaves turgidity, and remote/proximal sensing data were collected at the plot scale to analyze the crop response. The two cropping seasons were assessed as normal years with intermittent dry spells. The yield and the N uptake, in the two seasons, were affected by the supplementary irrigation, e.g. for the treatment 54 kg N/ha, an average increase in yield from 3.89 t/ha for non-irrigated plots to 4.86 t/ha when irrigated. The excess in N application was utilized by the increase in N uptake when irrigation was applied, e.g. the averages N uptakes in irrigated plots were 5-10% higher at a late growth stage as compared to non-irrigated plots for the same N rate applications. The growth time line, from phenology development assessment and the vegetation indices calculated from drone multiband images, showed that the growth in the trials with higher clay content was slower than those in sandy loam soil during the development growth period. This delay was recovered, and the crop reached comparable growth stages in all the blocks by the end of the mid-season period. The study showed that, under the Swedish conditions, even in normal years, the crop can be exposed to intermittent dry spells, reducing nutrient uptake and yield, and hence a near real time detecting, remotely or proximally, of the crop water status allows to spatiotemporally modifying nutrient and irrigation management to maximize fertilizer use and reduce potential environmental concerns due to untimely nutrient availability.

Keywords.

Water stress, within field management, precision N application, precision irrigation.

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Introduction

The food demand over the world is increasing due to the rapid increase in the population. At the same time, the direct and indirect effects of climate change are causing several abiotic stresses to crop growth and the environment. Abiotic stresses, for instance, drought, temperature variations, soil salinity, soil alkalinity and heavy metal stresses can have overwhelming impacts on the growth and productivity of crops under different agricultural ecosystems, which may develop constraints to food security worldwide. Developing solutions to deal with the increasing frequency of extreme weather events is a challenge for agricultural researchers (Kumari et al., 2022). In 2018, Sweden experienced an unprecedented drought that severely affected the agricultural, water, and energy sectors. During the period from June to July 2018, some regions experienced a significant reduction in precipitation as compared to a normal year. Krikken et al. (2019) showed a precipitation anomaly for July 2018 ranging from 0 mm to - 100 mm as compared to 1981–2010 climatology. In July 2018, some locations, such as Kastlösa in Öland and Komstorp in Blekinge, did not receive any precipitation, while others, such as Varberg and ¨Oland's southern cape, received 0.2 and 0.8 mm, respectively. This caused a drastic reduction in crop yields, including for key crops such as wheat, potatoes, and other forage crops (Campana et al., 2022). The lack of forage crops negatively affected dairy farms and related industry. Analysis of the Standardized Precipitation-Evapotranspiration Index (SPEI) for the period 1950–2020 indicates that 2018 was one of the worst droughts in more than 50 years for Swedish farmers (SPEI Global Drought Monitor, 2020). As a result, farmers had to start irrigating or installing irrigation systems. However, the scarcity of rainfall also severely affected the water resources available for agricultural production. Some counties, such as Skåne, issued restrictions on irrigation to preserve the scarce water resources, putting further stress on farmers, especially those who had water-intensive crops, such as vegetables and potatoes. In some cases, especially for those growers who did not have the possibility of irrigation, potatoes were unharvested due to the poor yield and potatoes size (Statistics Sweden, 2022).

Extreme weather definitions from a crop production perspective, should reflect impacts on germination, growth, development and survival of crops (Barlow et al. 2015), as well as conditions for crop management. A drought is a period of unusually persistent dry weather that persists long enough to cause serious problems such as crop damage and/or water supply shortages. The severity of the drought depends upon the degree of moisture deficiency, the duration, and the size of the affected area. There are actually four different ways that drought can be defined: 1) Meteorological: a measure of departure of precipitation from normal. Due to climatic differences, what might be considered a drought in one location of the country may not be a drought in another location, 2) Agricultural: refers to a situation where the amount of moisture in the soil no longer meets the needs of a particular crop, 3) Hydrological: occurs when surface and subsurface water supplies are below normal, and 4) Socioeconomic: refers to the situation that occurs when physical water shortages begin to affect people. Soil water status, which refers to the wetness or dryness of soils, is crucial for the productivity of agroecosystems, as it determines nutrient cycling and uptake physically via transport, biologically via the moisture-dependent activity of soil flora, fauna, and plants, and chemically via specific hydrolyses and redox reactions. Soil water status is most importantly controlled by atmospheric (e.g., rainfall, evaporative demand) and hydrologic (e.g., infiltration, soil water redistribution) processes but also by soil properties and related soil processes, land use and topography. The soil water status is typically described by the soil moisture content expressed on either a volumetric or gravimetric basis. The soil moisture content is related to the soil matric potential through the moisture retention characteristic function. The matrix potential of unsaturated soil is by definition negative (Bauke et al., 2022). Agrometeorological extremes consider the relation of potential and actual impact of weather events on crop development and yield. The definitions of agrometeorological extreme events used in literature are not standardized. Unlike meteorological and hydrological indices, agrometeorological indices need to reflect intra-seasonal frequency and intensity of events, to inform crop and animal husbandry management (Malmquist et al., 2022).

The aim of this study is to assessing, under the Swedish conditions, a probable within field water stress through assessing the spatiotemporal variations in:

- Soil profile water moisture content.
- Vegetation indices.
- Plant leaf turgidity.
- Nitrogen uptake.
- Crop yield

To achieve this aim, an experimental study was carried on at the SLU research station in Götala on oats crop for the two successive years 2020 and 2021. The experimental design consisted of five trials distributed in the field with topography and soil type base. Soil profile moisture contant, weather, crop's phonological and biological parameters and remote sensing indices were collected and analyzed in aim of assessing the water and crop status at within the field.

Materials and methodes

The study was carried out for two cropping seasons (2020-2021) in Spring Oates (Galant, SW 051020) at the SLU's research station in southwestern Sweden (Götala, 12ha, 58.378958N, 13.480354E) representing intense cereal production area. The field experiment was designed over five trials (blocks), to represent the main variations within the field based on soil type and topography. The area consisted of five field trials, named WSG 1-5, each measuring 15m by 11m. Within each trial, there were five treatments replicated three times, resulting in 15 plots for each trial (table 1 and figure 1). Each plot measured 3m by 3m, but only the centered 2m by 2m was sensors installation and harvest to avoid edge effect (figure 1).

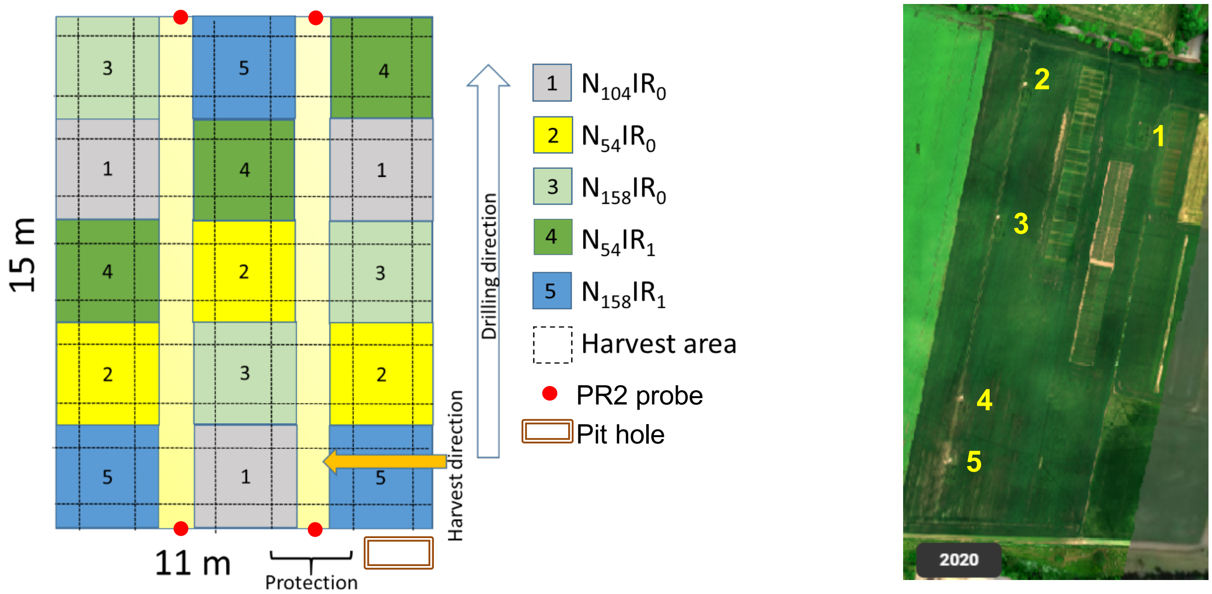

Figure 1. Left: E.g. of the random distribution in a trial, varies between trials. Five treatments (1-5), three replicates. 3×3m plot area, 2×2m harvest area. Right: location of the five trials within the field.

Table 1. Treatments' inputs (N rate application and irrigation) for the two years 2020 and 2021:

Treatment No.	2020-2021		
	Applied N (kg/ha)	Irrigation	Symbol
1	54+50	No	$N_{104}IR_0$
2	54	No	$N_{54}IR_0$
3	54+50+54	No	$N_{158}IR_0$
4	54	Yes	$N_{54}IR_1$
5	54+50+54	Yes	$N_{158}IR_1$

The irrigation was carried on twice each season (Irrigation amount 20mm each) based on the dry spells during the growth season (2nd and 12th June 2020, 11th and 17th June 2021). Local weather station was installed in the field, equipped with two sensors for air temperature and RH (ATMOS 14 at 1.5 m and VP-3 at 0.2 m), wind speed and direction, solar radiation and rainfall gauge. Data were registered every 15 minutes and reported to ZENTRA Cloud by GPRS every two hours (https://zentracloud.com/accounts/login/#/dashboard_map). 180 kg oats (Galant) were sown with 200 kg/ha Axan N27 (54 kg N/ha) in April (April 2nd for the year 2020 and April 17th for the year

2021), followed one or two doses (50, 54 kg/ha) depending on the treatment (Table 1). Soil profile moisture was followed up using four PR2-profilprob (from www.delta-t.co.uk) installed at the edges of each trial, as shown in figure 1. Volumetric water content (VWC) measurements using PR2 with a time step varies from one day to few days bases on the water input (rainfall, irrigation). Soil moisture was also measured on soil samples using the oven, for PR2 calibration purpose, when soil was sampled for texture analysis. Intact soil samples were sampled for three depth (0-30, 30-60 and 60-90cm) for measuring the soil water characteristics (soil density, porosity, permanent wilting point 'PWP' and field capacity 'FC'), available water (AW=FC-PWP) was calculated for each layer. A pit hole was excavated at the edge of each trial (figure 1) to follow up the root depth at different growth stages (Shallow groundwater level was observed in WSG-4 and 5, as shown in figure 2). To follow the water stress status in the crop, the water turgidity in the leaves was indirectly measured using a leaf thickness sensor from (https://www.agrihouse.com/) (Figure 2). Measurement were always taken about the same time of the day (late in the afternoon) with a time step varies from one day to few days bases on the water input (rainfall, irrigation). This sensor was installed on all replicates and treatments.

Figure 2. Left: leaf thickness sensor from https://www.agrihouse.com/, middle: Pit hole WSG-5, right: Pit hole WSG1.

Remote sensing during the growth period (even in late season) was carried on by a drone equipped with a camera with five wavelength bands in the red edge-NIR sensor (Micasense Altum; MicaSense, Inc. Seattle, WA). In 2020, five flights were affected (May 5th and 22nd, June 3rd and 16th and July 2nd) (DC-13, 25, 32, 51, 72 respectively), while in 2021 the flights were limited on two (10th and 14th June) during the growth stages DC-32 and 43 respectively. The N uptake was assessed using the N tester from Yara. Measurement were carried on three times each year, June 10th, 14th, 21st (DC≈39, 40 and 53 respectively) in the both years 2020 and 2021. In the middle of august, the inner area (2×2m) of each plot was harvested and the yield was estimated.

In this study, the weather data was analyzed at rainfall event and monthly amount bases, compared between the two years. The drought indicators (dry year, drought period and dry spells) were analysed from agricultural perspective (Malmquist et al., 2022):

- Dry summer, $P<40$mm in May and June.
- Drought period, $P<10$mm and no more than 4 days rainfall during 14 days.
- Dry spell, at least 5 successive days with daily $P<1$.

At each trial, and for each depth (10, 20, 30, 40, 60 and 100cm), one average value of VWC was calculated from the four PR2 props and compared to the PWP and FC at that depth. Time series were drown to detect the periods of water shortage ($VWC<0.3\times AW$) in the soil. The experimental setup is not designed to collect VWCs measurements at treatment base, so the comparison was limited at trial base to give an idea about the water availability variations within the field under non-irrigated conditions. The water status in the soil profile was compared with the readings of the leaf sensor to figure out if this sensor can reflect the water status in the crop. On the other hand, Comparison between clips installed on plants from irrigated and non-irrigated plots was carried on to assess how irrigation could affect the water status in the crop. The drone data was statistically analyzed using Solvi platform (https://solvi.ag/) at plot and treatment (average of replicates) bases by calculating the average of different available vegetation indices in Solvi (e.g. NDVI 'Normalized difference vegetation index'; Rouse et al., 1974). At treatment base, the vegetation indices evolution curves were drawn and compared between trials to detect the variations in growth stages within the field. The average values at the treatment base of the N tester measurements (µmol of chlorophyll per m^2 of leaf) were compared between treatments at the trial base and between trials for the same treatment, results were assessed based on the general guide, from Yara on cereals (https://www.yara.co.uk/crop-nutrition/farmers-toolbox/n-tester-bt/):

- An N-Tester BT reading above 700 suggests the crop has sufficient N.
- Reading below 650 suggests the crop is likely to be deficient.
- Between 650 and 700 requires a judgement based on recent N applications, previous organic manure/slurries, current weather and growing conditions and whether the 3 digit value has increased or decreased since the previous reading.

The comparisons between the treatments within the trials reflect the effect of the N application rate and the irrigation on the crop growth parameters and production at the trial placement, while the comparisons between the same treatments between trials reflect the site-specific effect within the field.

Results

Figure 3 shows the daily precipitation (P) events in both years between April and August. The amount of P registered in 2020 was 286 mm, where in 2021, it was 206 mm. As observed in Figure 4, there was a notable increase in the monthly P levels from mid-May through the end of the season in 2020, and a heavy rainfall for two days in June 21st-22nd. In 2021 there was less rainfall in June comparing to May and July. In 2020 and 2021, despite not being classified as dry summers, there were periods of drought and dry spells. In 2020, there were seven dry spells and three drought periods, while in 2021, there were seven dry spells and two drought periods (see table 2).

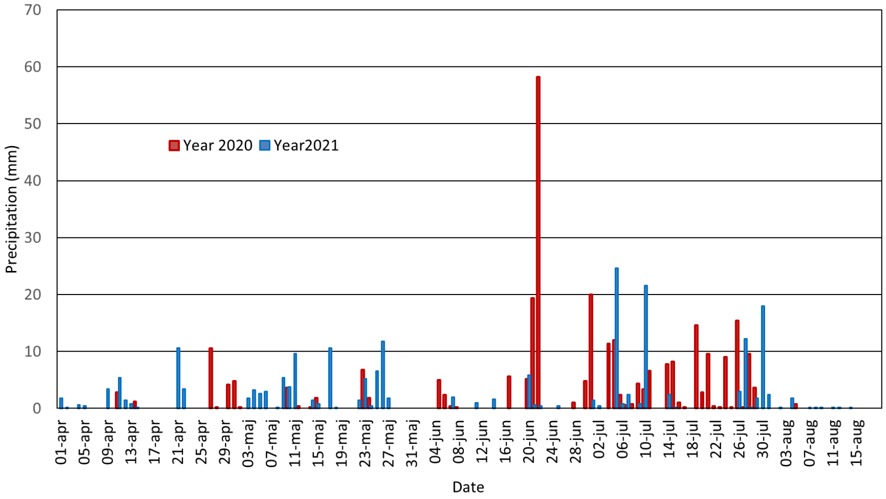

Figure 3. Daily precipitation, Götala 2020 and 2021 (Local weather station).

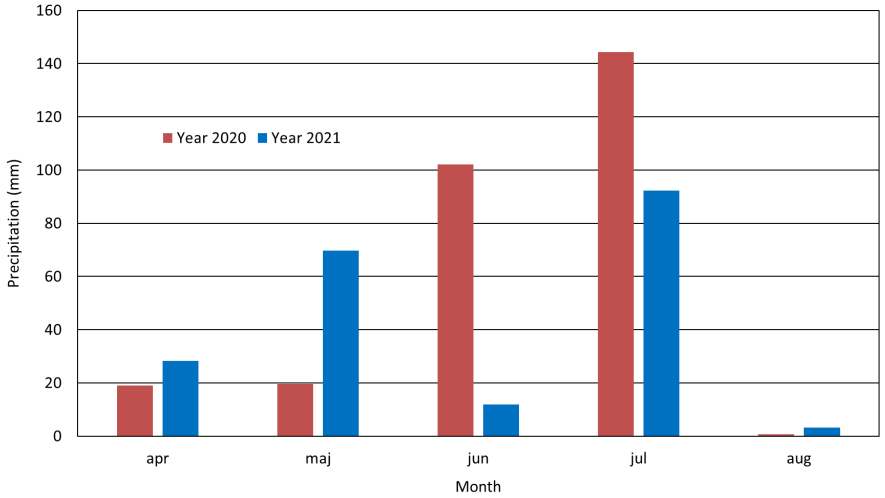

Figure 4. Monthly precipitation, Götala 2020 and 2021 (Local weather station).

Table 2. Drought and dry spell, Götala 2020 and 2021.

2020		2021	
Drought	Dry spell	Drought	Dry spell
8 April - 26 April 25 May- 16 June 29 July – 18 August	15 April - 26 April 2–9 May 16-22 May 25 May- 4 June 7-16 June 23-27 June 30 July - 17 August	28 May – 19 June 11 July - 26 July	14-20 April 23 April - 2 May 28 May – 6 June 15-19 June 22-30 June 15-25 July 5-11 August

The soil type at different depths, up to 650 mm, in the trials WSG1- 4 was Sandy Loam, with an average clay content 15% and average sand content 62%. The trial WSG5 had higher clay content; it was sandy clay loam 30-80mm (clay 26%), clay loam 300-350mm (clay 38%) and silty clay 600-650mm (clay 44%). The trials had differential elevation of about 2.4m, WSG1 is the highest and WSG5 is the lowest. For the two years, the soil profile in the trials WSG4-5 was relatively wetter than in WSG1-3. The top layer (10-100mm) in all the trials reached once the PWP (zero AW) during the whole growth season (drought period May 25th – June 16th in 2020 and May 28th - June 19th in 2021, see e.g. figure 5). The water content in the deeper layers followed the same shape with gradually higher values of AW (e.g. In the layer 300-400mm the water content reached 25% of the AW during the above mentioned drought period, in deeper layers, the water content didn't drop below 50% of the AW). On the other hand the total water content in the whole profile did not drop below 50% of the AW in WSG1-3 while it stayed very high (near the FC) in the WSG4-5, see figure 5.

The leaves clips reflected the water status in the leaves; it shrank when there is less water input and swelled when more water is available, the response is mostly instantly (few hours delay). Non-irrigated plots, for all the N treatments, showed the same tendency responding to rainfall inputs, the leaves shranked considerably during the dry spell 7-16 June 2020, and recover again when the heavy rainfall happened on 20th June. While the irrigated plot showed more stable water status and less thickness variation with time (see e.g. in figure 6). The attachment of the sensor on the leaf is sensitive and the measurement should be taken with care, not to remove the sensor from its place. In some leaves the placement of the sensor on the leaf is harmed and became yellow after a period of 3-4 weeks, in this case another leaf is selected to re-install the sensor. Some sensors were removed by animals, even some animals tried to eat them when they noticed them.

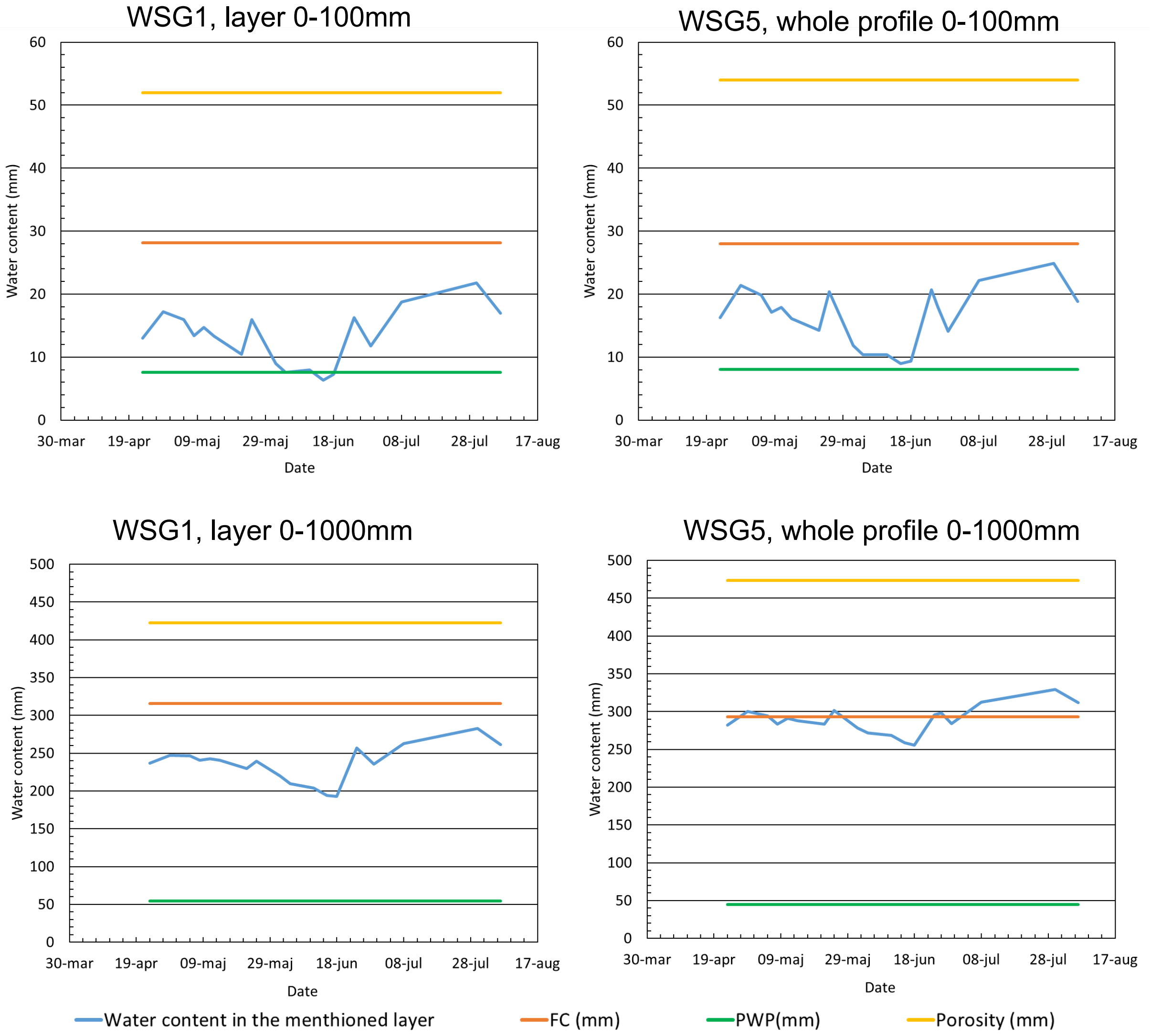

Figure 5. Comparison of the variations in the water content, between two trials WSG1 and WSG5, for the top layer 0-100mm and the whole profile 0-100mm.

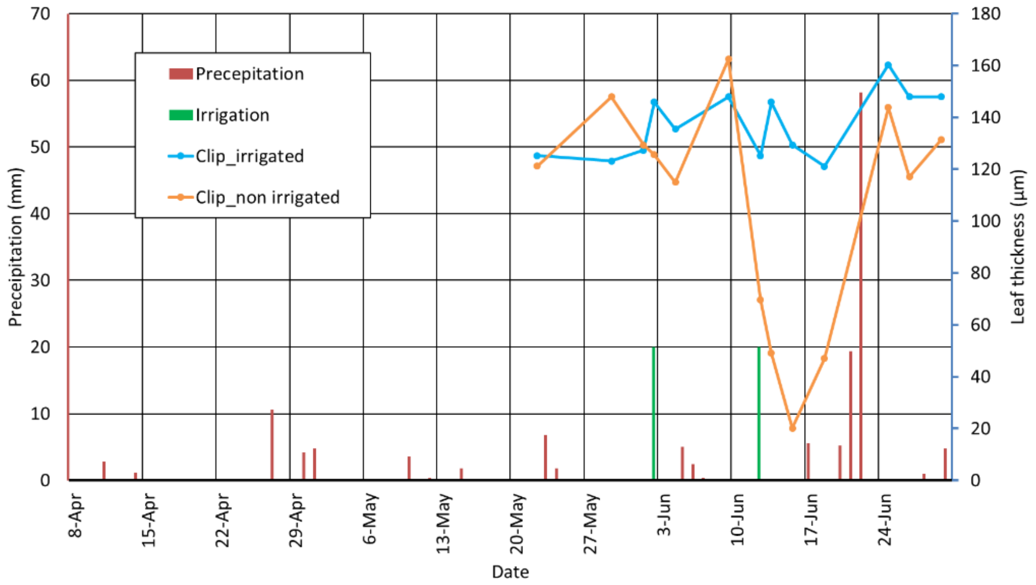

Figure 6. Example of Leaf thickness variations using the leaf sensor in irrigated and non-irrigated plots. Year 2020, trial 3.

For the two years 2020-2021, the chlorophyll concentration at the first measurement (June 10th 2021, DC≈39) was slightly less than 600 on Yara tester for all treatments in all trials, considered deficit in N (Yara guideline). The value for the treatment $N_{158}IR_1$ was less than the same treatment without irrigation ($N_{158}IR_0$), which shouldn't be the case, see figure 7 for the year 2020. For the date June 14th(DC≈40), in WSG1 the difference between the extra fertilized plot showed higher chlorophyll concentration than the reduced fertilization, while in WSG5 they looks similar. At the last measurement (June 21st, DC≈53), in booth WSG1 and 5, the extra fertilized plots with irrigation reached the limit judge sufficient N by Yara guideline (>700 µmol/m^2).

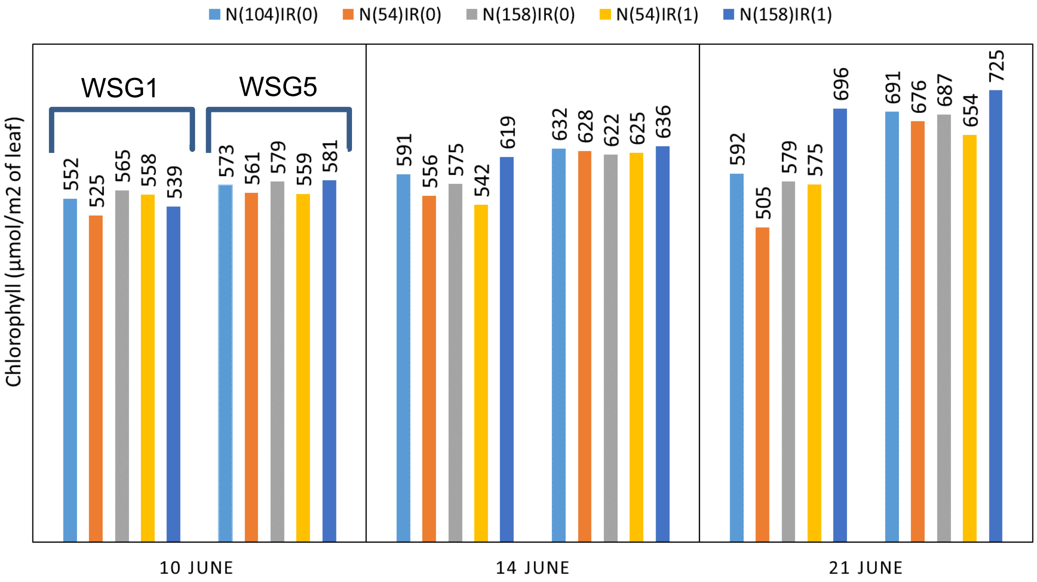

Figure 7. Average Chlorophyll concentration in the leaves, at treatment base in WSG1 and WSG5, measured by Yara N tester at three dates 10th,14th and 21st June (DC≈39, 41 and 53 respectively). Year 2020.

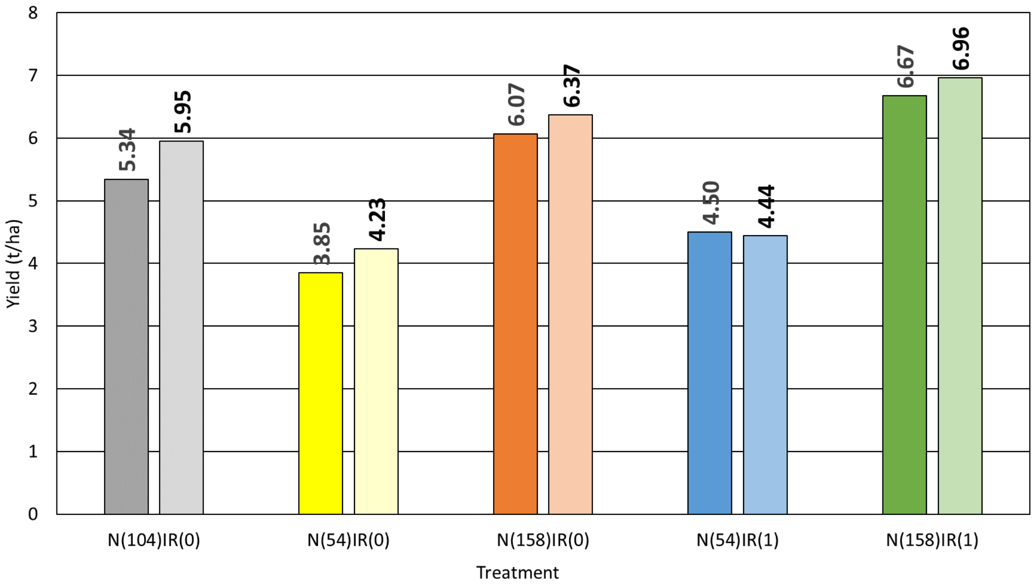

Figure 8. Average yield at treatment base in two trials WSG1 (dark color) and WSG5 (light color), Year 2020.

The yield measurements showed in general for all the trials higher yield for the two treatments with high N application for both irrigated and on-irrigated plots ($N_{158}IR_0$ and $N_{158}IR_1$) with superiority for the irrigated plots (e.g. for the treatment $N_{158}IR_1$ the yield was 6.67 t/ha, 0.6 t/ha higher than the same treatment but without irrigation $N_{158}IR_0$), see figure 8. When comparing between trials, the trial WSG5 showed higher yield for all the treatments when comparing between trials, even for the treatments without irrigation (figure 8). Similar results obtained in 2021.

The growth was faster in the trials 1, 2 and 3, where the soil has less clay content and the ground water was deeper. The same phenomena was applicable for all the treatments. The growth accelerated in the trial 4 and 5 in the beginning of June to reach the same growth stage in the other trials by the end of June. Figure 9 shows the evolution with time of the average NDVI value for the treatment $N_{158}IR_1$ in all the trials, see figure 9.

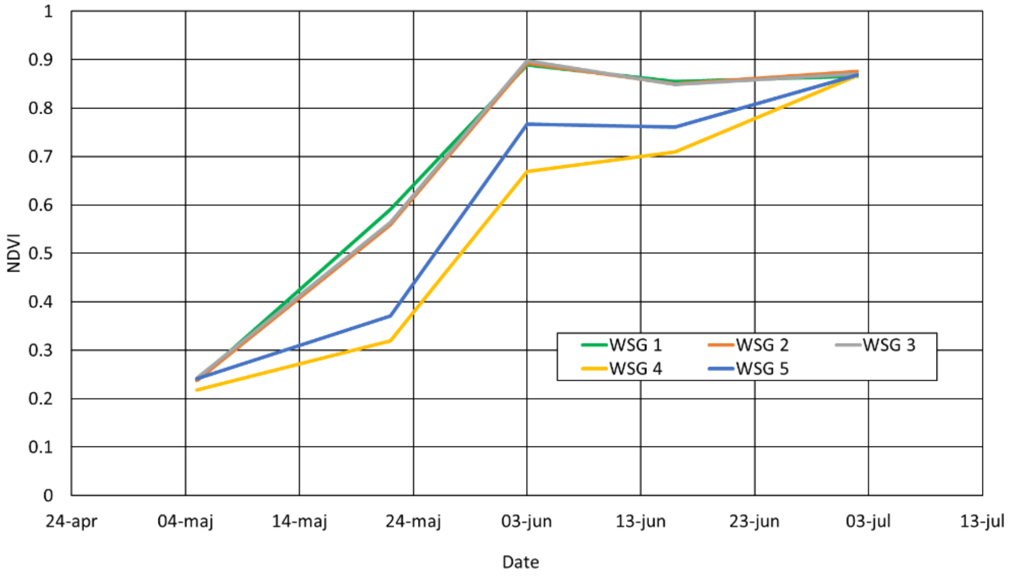

Figure 9. Average NDVI values of the three replicates, from drone flights, treatment $N_{158}IR_0$ for the whole growth period, year 2020.

Discussion

The two study summers were classified non-dry summers with occurrence of drought periods and dry spells. The results in this study showed that the variation within the field (e.g. soil type, topography, groundwater level) affect the growth progress, the soil water availability and the final yield. In all trials, the soil water content in the top layers (up to 200mm depth) reached the PWP only during the occurrence of a dry spell (end May - begging Jun, for both years). The budget of the water content in the whole soil profile 1m depth did not drop below 50% of the AW. In WSG 4-5 (situated in the lower topographical area within the field), where the soil varied from Sandy Clay Loam to Clay Loam and the groundwater was shallow (60-80 cm), the profile water budget didn't drop below 70% of the AW. These local conditions within the field led to a lake time in the growth evolution where WSG4-5 was slower than the other trials especially in the early season (May-June) where the second and third fertilizing was affected. The slower growth speed in the zone of WSG4-5 could be also attributed to the higher clay content than the other trials' zones, this delay was recovered in the late season, similar results obtained by Gulser et al. (2010). This variation were recognized by field growth stage assessment and equally by remote sensing using the drone. Taking into account, this delay in the growth allows optimizing the fertilization according to the variations in the growth stage within the field. This delay was recovered in the later season (June and July). The water shortage in the soil profile was detected clearly by the leaf sensors, which means that the depletion degree can be followed by measuring indirectly the leaves turgidity. This type of sensors is usually used on broad leaf plants, using it in cereal crops showed the need to change its placement on the same leaf or on another leaf because of the fragility of the leaf texture and the leaves senescence. The response of each sensor should be assessed individually (No averages between replicates can be taken), because the thickness of the leaf varies from leaf to another even at the same plant, measuring a time series of the leaf thickness reflects the turgidity variations in the leaf (plant) and shows the evolution of the water status in the plant.

According to Yara recommendations guideline, only the two treatment with extra N reached the sufficiency in N, the chlorophyll concentration when irrigate ($N_{158}IR_1$) was higher than without irrigation ($N_{158}IR_0$). In this case, the irrigation made more N available for the crop. Reducing N rate, with and without irrigation, judged as insufficient N application, irrigation couldn't make more N available for the crop, as it is limited in the soil. In the trials WSG4-5, more water was available in the soil profile because the groundwater was shallow (less than 1m) which made more N available comparing to the same treatments in the other trials. The yield varied between trials and between treatments within the same trial. It was higher in the treatments with extra N and maximum when it is irrigated. The yield in the trial WSG5 was higher comparing with the other trials, more water was available from the shallow groundwater for the whole growth period. Irrigation increased the yield even in the treatments with reduced N by making it more available to the plant. As the two seasons were not classified dry, so the variations in the yield were not extremely high (ranged between 300-600 kg/ha).

Conclusion

In Sweden, the growing season (for winter and spring crops) is the summer. Because of climate change, drought and dry spells are more frequent in the last decades and this affect to large extent the productivity. The variable N rate application is widely studied as the main limiting factor, without taking into account that the water as also a limiting factor even under the considered wet conditions in Sweden. In this study, although the two summer seasons were classified not dry with intermittent dry spells, adding irrigation as an input made more N available in the soil for the crop and increased the yield. The effect of irrigation varied within the field according to other site specifications (e.g. soil type, topography and groundwater level, applied N rate). The increase in the N uptake when applying irrigation, or when more water is available from groundwater in parts of the field, reduces the negative impact of over fertilizing. The yield increase varied of a range 300-600 kg/ha when applying irrigation. Detecting the water shortage in the soil profile was possible by using leaf thickness sensors, this makes it possible to multiply the check points within the field for a better zoning of water status for better within field irrigation management. The recommendation for using such leaf sensors in cereals is to change the placement of the sensor on the leaf (or change to another leaf) every 3-4 weeks because of the fragile texture of cereals' leaves and leaves senescence. To reach the yield potential and optimize the N uptake in a field, the variable water status within the field should be taken in consideration as a limiting factor even under the Swedish conditions. The variation in the yield's increases within the field, under different water status, showed that the yield gap will increase with drier seasons.

Acknowledgments

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