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Evaluating the suitability of a new telemetric capacitance-based measurement system for real-time application in irrigation and fertilization management

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Abstract: The suitability of a new wireless smart farming system for controlling irrigation and fertilization of horticultural plants was assessed in the study. The system (name: AGREUS®) includes sensors (soil moisture, salinity, weather data), executive modules (valve modules), and an application available on the web portal (accessed through computers and mobile devices). The studies were performed under laboratory and field conditions. Laboratory tests included appraisal of the precision of soil moisture and salinity measurements carried out with the soil probe (comparison with the results obtained by laboratory methods). Operational tests were conducted in field trials. In these trials, assessment of the possibility of practical control of irrigation and monitoring soil salinity was performed in an apple orchard. The conducted analyses have shown the usefulness of the system, not only for automatic control of irrigation but also for making decisions about the necessity to fertilize plants. The system enables continuous monitoring of changes in soil moisture and salinity, including the migration of minerals across the soil profile (using a probe with several measuring elements) as a result of the applied irrigation or rainfall. The system allows for automatic application of irrigation or fertigation depending on the adopted soil moisture and salinity thresholds. However, the tests showed that a salinity index calculated by the system does not directly correspond to the salinity values determined by laboratory methods. For this reason individual interpretation and determination of optimal ranges for plants is required.

Keywords: electrical conductivity, fertigation, salinity, soil moisture

INTRODUCTION

The growth in food demand, decreasing water resources and increasing contamination and degradation of the soil environment have been a driving force to develop new technologies for efficient use of water and fertilizers in agriculture. Water and nutrient deficiencies are major causes of stress and reductions in crop yield and quality. Farming systems should be more sustainable to reach economic and social profitability as well as environmental preservation. In many arid and semi-arid areas, water scarcity significantly limits the actual ability to produce food. The problem is aggravated by climatic changes, especially the increase in temperature, which negatively affects the climatic water balance.

The profitability of producing irrigated crops is directly related to water management. Irrigation scheduling based on measurements or estimations of crop water needs is one of the most important practices for irrigation management. Proper water management will increase yields and improve crop quality, conserve water, save energy and reduce environmental pollution. Much research has focused on quantifying plant water use and on establishing optimum schedules in irrigated crops (e.g. Rolbiecki and Chmura [2015], Treder *et al.* [2015 a, b], Żarski *et al.* [2011]).

A number of methods are available to assist growers in determining when water is needed and how much is required. One is to characterize soil/substrate water status by measuring water content or water potential. Because the soil moisture level determines the process of plant growth and development, accurate knowledge of its field-scale variability is important for improving irrigation management strategies with respect to crop production and optimal use of available water resources [ALI, MUBARAK 2017; VEREECKEN *et al.* 2014].

In addition to environmental factors such as temperature, light and water availability, the level of crop yield is also significantly influenced by the mineral abundance in soils or horticultural substrates. Obtaining high yields is possible only with the optimal use of fertilization, which is an important component of production costs. Fertilization not only significantly affects production costs but can also have a very negative impact on the natural environment [ROGOVSKA *et al.* 2019]. A parallel problem with decreasing amounts of precipitation and increasing evapotranspiration is the increase in soil salinity, which additionally reduces the productivity of plants. Salinity problems occur under all climatic conditions and can result from both natural and human-induced actions [ZAMAN *et al.* 2018].

The disadvantages of traditional monitoring of soil moisture and salinity that has been used to maintain their optimal levels are that it requires regular measurements, which can be time consuming. The use of appropriate sensors to continuously monitor soil moisture and salinity will help to make better use of water and fertilizers. The only way to solve or reduce the effects of the problems facing the current agriculture is the wide use of modern technologies that fit into the concept of precision agriculture [MULLA, YUXIN 2015].

Soil moisture sensing technology has been available to the irrigation market for many years. However, its adoption into common usage has been very slow, possibly because of the low quality measurements produced by some sensors and the high price of others. To be viable, a soil moisture sensor must be accurate and reliable, and also affordable to the end user [CAMPBELL *et al.* 2009; TREDER, KLAMKOWSKI 2008].

Among the sensor types available on the market, dielectric sensors that measure the relative permittivity (dielectric constant) of a medium are increasingly being used as a tool for monitoring soil/substrate water content. The dielectric constant is, approximately, 3–5 for a dry soil, 1 for air, and 80 for water. Thus, changes in the moisture content cause a substantial change in the dielectric constant of the soil. Calibration equations correlate the dielectric constant with soil moisture content. The availability of various sensor models, their decreasing cost and the possibility of measurement automation are the main factors explaining the success of this technique.

The currently proposed technical solutions allow measurements of not only soil moisture but also its temperature and electrical conductivity (*EC*), which is of key importance for precise fertilization and cultivation on saline soils (multi-parameter sensors) [BURNET, VAN IERSEL 2008; HILHORST 2000; KARGAS *et al.* 2011; ROGERS *et al.* 2008; ZAMAN *et al.* 2018]. Modern technical solutions using the Internet of Things (IoT) technologies allow long-term operation of wirelessly communicating battery- or solar-powered sensors. Suitably positioned sensors for measuring soil, climate, and other parameters can become a source of data for agrotechnical decision support systems in areas covered by the metering [JAYARAMAN *et al.* 2016].

The aim of the research undertaken is to assess the suitability of the new AGREUS® telemetric irrigation and fertigation control system for monitoring soil parameters, and for controlling irrigation and fertilization of horticultural plants.

MATERIAL AND METHODS

- Description of the AGREUS® system

AGREUS® (developed by INVENTIA, Poland) is a wireless smart farming system that enables the acquisition of measurement data to facilitate making agrotechnical decisions, as well as for control. The system includes dedicated sensors and executive modules, and an application available for desktop computers and mobile devices (Fig. 1).

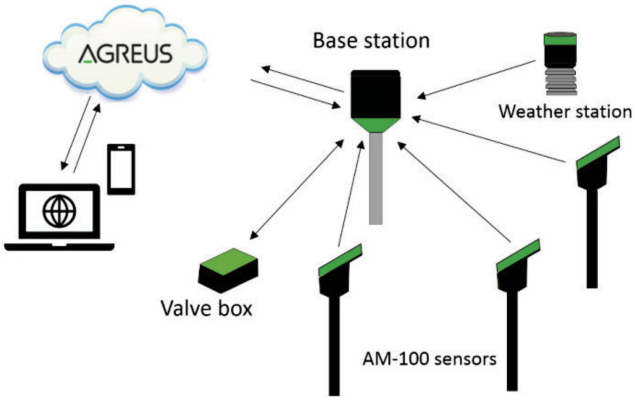

Fig. 1. Schematic diagram of the AGREUS® system; source: own elaboration

- Base station

The base station provides wireless transmission between the measurement and executive modules on the company's web portal. Communication between the base station and the sensors takes place via the Semtech LoRa® wireless radio network.

- Sensors

AM-200 – wireless sensor for remote monitoring of temperature, air humidity and leaf wetness.

AM-100 – wireless, solar-powered multi-parameter sensor for use in soils and soilless substrates. It measures the dielectric properties (using 40 MHz frequency capacitance technology) of the soil/growing medium and calculates: water content, electrical conductivity (*EC*) of water in soil pores (EC_p), salinity index (*SI*) and temperature. Depending on the version of the sensor, measurements can be carried out on one, two or three levels (every 10 cm). In the settings, the user can select calibrations for various types of soils and horticultural substrates (light soil, heavy soil, perlite, peat substrate, coconut substrate). The manufacturer does not provide the models according to which the water content and salinity parameters are determined.

- Controllers

The AM-421 and AM-411 valve modules are used to control irrigation and fertigation with valves powered by 24 V AC or 9 V DC.

- Web application

The software included in the system allows the processes to be controlled depending on the threshold values entered by the user. Each of the measured parameters can have a real impact on the automatic management of irrigation and fertigation, or support decisions related to the need to manage irrigation and fertilization.

- Measurements and observations

As part of the assessment of the suitability of the AGREUS® system for monitoring soil parameters and irrigation and fertilization management in horticultural cropping systems, studies were performed under laboratory and field conditions.

The quality and practical suitability of the entire irrigation and fertilization management system (fertigation) largely depend on the reliability of the soil measurements; therefore, in the first stage, the quality and repeatability of the measurements carried out with the AM-100 soil probe were assessed.

Laboratory tests compared the results of soil moisture and salinity measurements carried out with the AM-100 probe with the results obtained by laboratory methods. The measurements and tests were carried out on a light soil (loamy sand in texture).

Soil samples of different moisture content were placed in 5 dm^3 pots. Soil moisture was measured in thus prepared samples using the AM-100 probe. The actual moisture content of the samples was determined by the oven-dry method. The soil samples taken from the pots (in 100 cm^3 cylinders) were weighed and dried at 105°C until the weight stabilized. The moisture content as a percentage of the volume is calculated by the formula:

$$W_v = \frac{d_1 - d_2}{V} 100 \tag{1}$$

where: W_v = moisture content by volume (%); d_1 = mass of the cylinder with moist soil (g); d_2 = mass of the cylinder with dry soil (g); V = cylinder volume (cm^3).

The correlation between soil moisture and soil water potential was also determined. The data for the analyses were obtained by simultaneous measurements of moisture and water potential of slowly drying soil. The measurements were carried out in specially constructed openwork containers. Soil moisture was measured with the AM-100 probe while the water potential was measured with a tensiometer with an electronic read-out (Blumat Digital model).

In subsequent tests, the usefulness of the AM-100 probe for measuring soil salinity was assessed. To produce varied salinity levels, different amounts of the soluble 19-6-20 Kristalon Blue compound fertilizer were added to the soil samples. In the soil prepared in this way, EC_p and SI were measured using the AM-100 probe, while the salinity of the soil was determined by the laboratory method. The EC (mS·cm^{-1}) and salinity (g·dm^{-3}) of the soil were determined in a suspension of the soil in distilled water (1:2 v:v) using a HI991301 conductometer (Hanna Instruments).

Operational tests of the AM-100 probe were performed in field trials. The trials assessed the possibility of practical control of irrigation and monitoring of soil salinity changes under the influence of irrigation and rainfall. The trials were carried out in the Experimental Orchard (Pomological Orchard in Skierniewice) in an apple-tree plot where AM-100 probes were installed so that the measurement sensors were at a depth of 10 and 20 cm. Drip irrigation of the apple-tree plot was carried out automatically with the help of software available on the AGREUS® portal. The irrigation program was so configured that the system would begin watering at a specified time when soil moisture measured at a depth of 20 cm fell below the defined (in laboratory tests) threshold corresponding to the optimal water availability for plants (for a water potential of approx. –30 kPa). To assess the dynamics of soil salinity changes using the AGREUS® system during plant cultivation, two fertilization variants were used: (i) control without additional fertilization, (ii) a high dose (for high dynamics of salinity changes) of top-dressing with 19-6-20 Kristalon Blue at 52 g·m^{-2}.

In order to assess the relationships between the analysed parameters, regression analysis was used. The relationships were evaluated using simple linear models. Correlation coefficients were used as a measure of the model's fit. Calculations were performed using Excel spreadsheets.

RESULTS AND DISCUSSION

In the initial work performed in the laboratory the accuracy of soil moisture and salinity measurements carried out with the AM-100 probe was assessed. The tests showed a high correlation between the actual soil moisture content (determined by the oven-dry method) and the measurement data obtained with the AM-100 probes (Fig. 2).

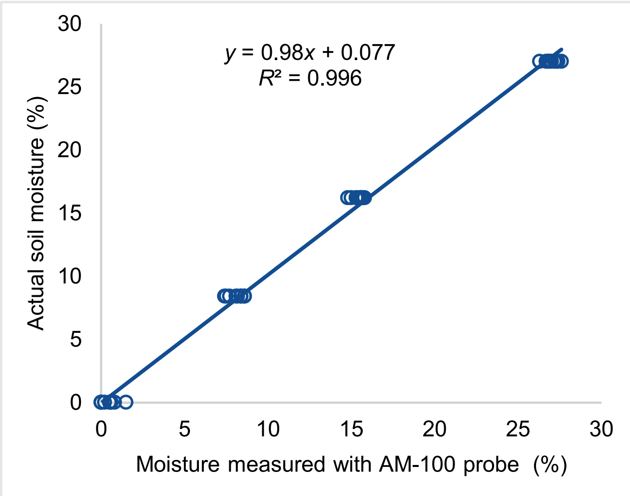

Fig. 2. Correlation between actual soil moisture and that measured with AM-100 probes; source: own study

Measuring water content in real time can only be done through an indirect method, which is measuring another soil property that correlates with soil water content. One of the possible properties possible for such measurement is soil dielectric constant (relative permittivity). To obtain a soil water content value from dielectric soil measurements, it is necessary to perform calibration specific to a given soil (or soilless growing medium). Results of numerous studies have proved that (after proper calibration) this type of sensors can be useful as a reliable moisture monitoring tool in sustainable use of water resources in agriculture (irrigation scheduling) and is suitable for building large-scale agricultural wireless sensor networks [Huan *et al.* 2017; Kennedy *et al.* 2003; Klamkowski, Treder 2017].

Data on the amount of water contained in the soil do not provide information about its availability to plants. To schedule irrigation, both soil water potential and soil water content should be monitored to learn when to trigger irrigation and how much water is needed. This study determined the correlation between soil moisture and its water potential (Fig. 3). The water potential has been widely used as an indicator of plant water status in ecophysiological studies and has been proposed as

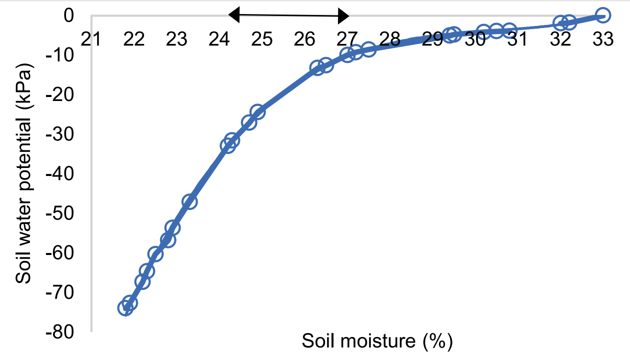

Fig. 3. Correlation between moisture content and water potential for light soil; arrow indicates easily available water range; source: own study

a monitoring method for irrigation management purposes [BITTELI 2010]. To ensure a soil moisture content in the range of readily available water, the soil water potential should be kept in the range of −10 to −30 kPa. Plant growth inhibition begins when the water potential reaches the level of −70 kPa. The demonstrated correlation allows a reliable assessment of water availability, which is useful for controlling irrigation and determining critical periods for plants [BIANCHI *et al.* 2017; BITTELLI 2010]. On the basis of the obtained results, the value of 24.5% (by volume) was assumed in the field trials as the threshold value of optimal soil moisture for plant development (for the water potential of −30 kPa; Fig. 3).

The laboratory tests also determined the precision of soil salinity measurements carried out with the AM-100 probe. A high correlation was demonstrated between the measurements of soil electrical conductivity performed by the laboratory method (determined in a suspension of the soil in distilled water (1:2 v:v) and the measurements of EC_p (pore water *EC*) carried out with the AM-100 probe (Fig. 4).

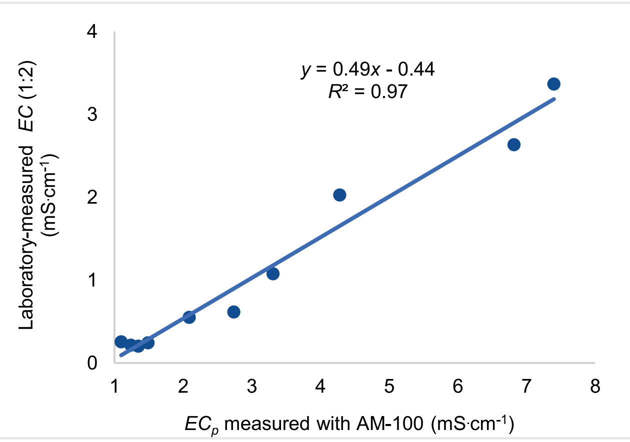

Fig. 4. Correlation between the measurements of electrical conductivity in soil pores (EC_p, AM-100 probe) with the measurements of soil *EC* determined by the laboratory method; source: own study

Because soil salinity, measured both by the laboratory method and with soil probes, is determined directly from electrical conductivity measurements, the two parameters (salinity and *SI*) are closely correlated with each other (Fig. 5). The linear regression model describing this correlation (salinity = 2.35*SI* − 0.87) determined in the trial indicates that the *SI* equal to 1 corresponds to the laboratory-determined salinity at a level of 1.48 g of NaCl per dm^3 of soil, while *SI* = 2 corresponds to very high salinity (3.83 g of NaCl per dm^3 of soil), dangerous for the cultivation of plants. At such high values of soil salinity (*SI* ≥ 2), the authors had observed the death of bean plants (in trials conducted on bean plants grown in containers, data not presented). The obtained results prove that the values of the *SI* parameter do not correspond directly to the salinity values obtained by the laboratory method and therefore require individual interpretation and hence determination of optimal ranges for plants.

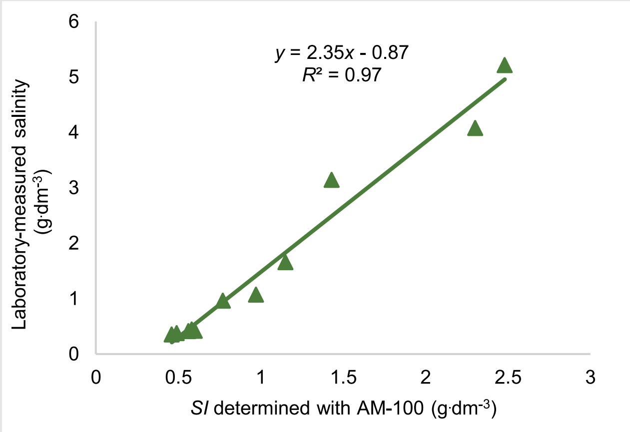

Fig. 5. Correlation between the soil salinity index (*SI*) and soil salinity determined by the laboratory method; soil measurements were carried out at a moisture level close to the field water capacity; source: own study

In scientific research and also in practice, many methods of determining soil salinity are used and, consequently, also many threshold (reference) values in cultivation recommendations for individual plant species. In laboratories, soil salinity (EC_e) is measured in aqueous extracts of saturated soil pastes prepared according to a standard procedure [RICHARDS 1954]. However, many laboratories determine soil salinity based on measurements of electrical conductivity (*EC*) with 1:2, 1:2.5 or 1:5 soil-water extracts ($EC_{1:2}$, $EC_{1:2.5}$, $EC_{1:5}$) because it is a simpler procedure than with the standard saturated paste extract (EC_e). Because interpretations of crop tolerance and remediation of salinity are based on values derived from EC_e, it is necessary to convert $EC_{1:2}$ $EC_{1:2.5}$ or $EC_{1:5}$ to EC_e in order to evaluate plant response and plant management activities [ABOUKILA, NORTON 2017]. Procedures for field assessment of soil salinity are described and factors to convert *EC* of different soil:water (1:1, 1:2.5, 1:5) suspensions to electrical conductivity of saturated paste (EC_e) from different regions are tabulated and provide useful information to those adopting such procedures [AKRAMKHANOV *et al.* 2008; SHAHID *et al.* 2013; SONMEZ *et al.* 2008; ZHANG *et al.* 2005].

Different meters available on the market determine the salinity of soils and horticultural substrates according to different parameters. For example, the WET sensor (Delta-T Devices, USA) measures the bulk soil electrical conductivity (EC_b) and on the basis of this value estimates the EC_p of the water in the soil pores [INCROCCI *et al.* 2009; KARGAS *et al.* 2011]. Sensors manufactured by Sentek, e.g. Drill & Drop (Sentek Sensor Technologies, Australia), provide soil salinity values in abstract units called VIC (volumetric ion content). The measurement units of VIC can be quantitatively related (calibrated) to the soil *EC* through site-specific physical soil sampling and analysis [DALTON *et al.* 2018; STARR *et al.* 2009]. Another example is Field

Scout soil and water *EC* probe produced by Spectrum Technologies (UK), which permits direct measurements of EC_b in soil. For a better interpretation of this data, Ekwue and Bartholomew [2011] developed a calibration model relating the measurement data to those obtained in the laboratory (EC_e of saturated paste).

In this study, the assessment of the possibility of using the AGREUS® system for the practical control of irrigation and monitoring of changes in soil salinity was carried out in apple cultivation. The irrigation program was configured to make the system start irrigating at 2:00 p.m. provided that the soil moisture measured at a depth of 20 cm was below 24.5% (determined on the basis of the laboratory results). Based on the pattern of changes in soil moisture and rainfall, it can be concluded that the system controlled irrigation according to the adopted assumptions (Fig. 6). The very high dynamics of changes in moisture in the topsoil suggests that in the case of very young plantings and shallow-rooted plants, irrigation should be carried out according to measurements obtained at a depth of 10–15 cm.

Through the monitoring of environmental conditions and soil moisture, the AGREUS® system automatically makes the decision to irrigate, or it can be manually activated from the farmer's Web portal. The results obtained are very promising, representing a significant contribution to environmental sustainability. An automatically activated irrigation system promotes a practical response for efficient irrigation not only in agricultural production [Burnett, van Iersel 2008; Shufian *et al.* 2021] but also in landscaping [Caetano *et al.* 2015]. Thus, using it makes sense in every region of the world as it saves water, time and energy. Moreover, in order to optimize water efficiency, it is important to calibrate the decision formula for starting irrigation. In any case, to maintain a higher water potential of the soil, larger amounts of water have to be used [Burnett, van Iersel 2008]. However, knowing the plant's sensitivity to drought stress that changes during the growing season, the farmer can precisely control irrigation, increasing the efficiency of water use by appropriately lowering the moisture threshold at which irrigation will be carried out [Romero *et al.* 2010].

In the field experiment conducted in the apple-tree plot where the quality of irrigation control at a specific soil moisture threshold was assessed, soil salinity was measured at the same time. Monitoring of the changes in salinity in the soil profile showed a very high variability of this parameter throughout the entire period of measurements (Fig. 7). The salinity index was dependent on soil moisture content and the applied fertilization. An increase in salinity at a depth of 10 cm was observed on June 26, i.e. not until a month after the applied top-dressing fertilization. During the first two weeks of this period, there was virtually no effective rainfall, and no irrigation was applied. At a depth of 20 cm, an increasing trend in salinity was observed a week later (July 2). A spike-like increase in salinity at a depth of 20 cm was observed on July 27 after heavy rainfall had occurred. The result of direct

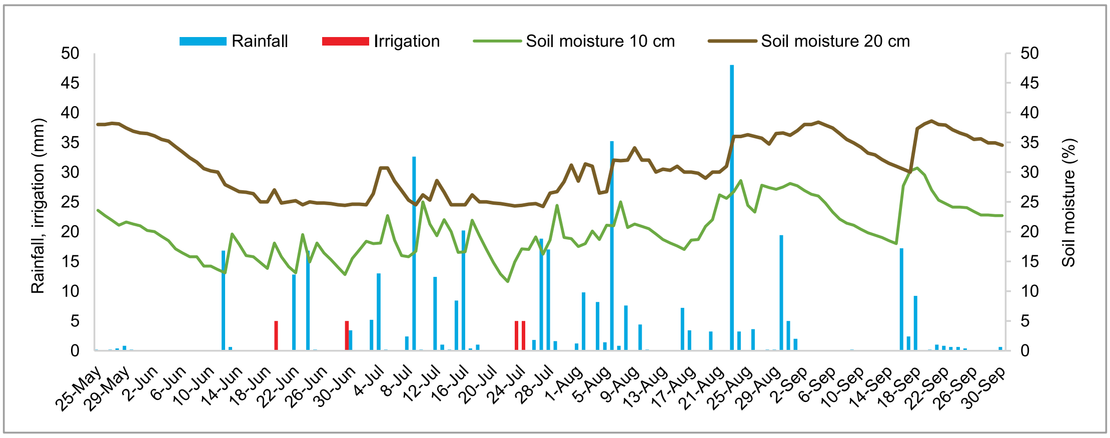

Fig. 6. Patterns of changes in soil moisture (at two depths: 10 and 20 cm) and in the occurrence of rainfall and irrigation in the apple orchard; source: own study

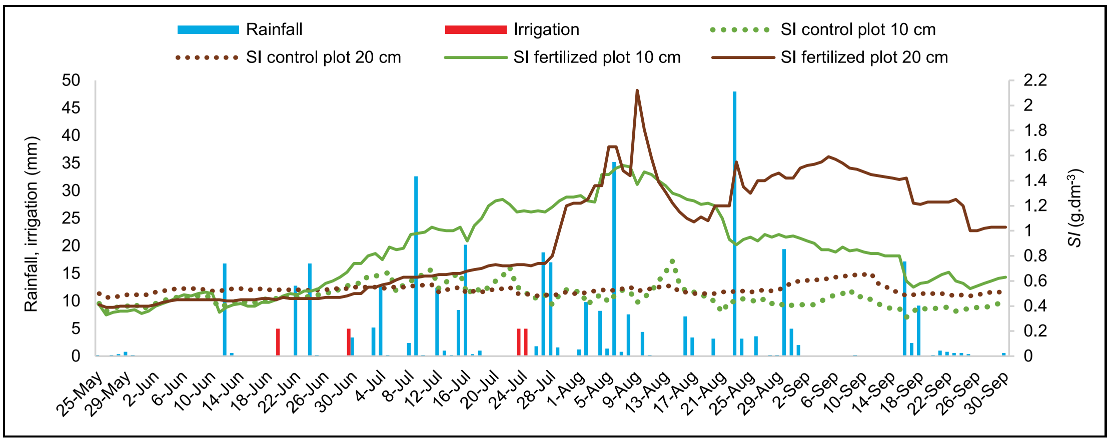

Fig. 7. Patterns of changes in the salinity index (*SI*) (at two depths of fertilized and control plots) and also in rainfall and irrigation in the apple orchard; source: own study

EC_p measurement, and thus the *SI*, is influenced not only by the amount of dissolved salts in the soil solution but also by the soil moisture content. A very low level of soil moisture is correlated to a high level of salt concentration. An increase in moisture content leads to a decrease in salt concentration and consequently in the soil *EC* readings. Therefore, comparative data for the interpretation of salinity changes in soil should be taken into account at a constant defined moisture level.

In a situation where a simultaneous increase in soil moisture and salinity index is observed, we can conclude about the actual increase in the amount of soluble salts in the soil. On August 23, there was a very high rainfall (48 mm) in the orchard, which resulted in significant migration of soluble mineral compounds deep into the soil profile. The salinity index measured at a depth of 10 cm decreased significantly with the increase in the value of this parameter at a depth of 20 cm. The presented data indicate the possibility of using the measurements of soil salinity parameters (EC_p and *SI*) as information helpful in crop fertilization.

Soil moisture and salinity sensors allow farmers to understand how water and fertilizers are being consumed by crops; they can also indicate the way water and salts interact with the soil and crop roots. This understanding, combined with observable in-field plant responses, helps agronomists decide when and how to irrigate and fertigate. Automated systems may allow growers to irrigate and use water and fertilizer more efficiently; if no excess water is applied, there will be little or no leaching of fertilizer salts. To use these new, efficient irrigation systems, growers must have information regarding the water requirements of different crops [Burnett, van Iersel 2008].

CONCLUSIONS

EC measurements are a good indicator of relative soil fertility levels, particularly if measured regularly and tracked over time. The conducted analyses have shown the usefulness of the AGREUS® system not only for automatic control of irrigation but also for making decisions about the necessity to fertilize plants. The system enables continuous monitoring of changes in soil moisture and salinity, including the migration of minerals across the soil profile (using a probe with several measuring elements) as a result of the applied irrigation or rainfall. The function of automatic application of fertigation depending on the adopted soil salinity threshold is very useful. It should be noted that the values of the *SI* parameter do not directly correspond to the salinity values that can be determined by laboratory methods. For this reason, they require individual interpretation and determination of optimal ranges for plants. Moreover, due to the characteristics of the measurements (correlations determined by the measurement technology used in dielectric probes), comparative data for the interpretation of salinity changes in soil should be taken into account at a specific moisture level.

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