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Visualization and quantification of peat substrate moisture by fully automated moisture controlling system (SMCS) in forest container nursery

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Abstract. This study explores the use of fully automatic monitoring system of peat moss substrate moisture under pine seedlings at Rudy Raciborskie forest nursery in the Silesian Upland. A brand new multipoint system for this study was created. The multichannel electronic recorder MPI-DN Metronic was the main part of the project. Twelve HD3910.2 probes (three electrodes) for volumetric water content measurement were used in a distributed configuration. Modbus RTU protocols were used for data transmission and the results were archived into an internal memory. One probe delivers 1440 measurements a day. Based on the average substrate moisture data from the field, the recorder controls the watering system according to the precisely defined parameters. Proper placement of sensors in the field allows for accurate analysis of the temporal and spatial variability of peat moss substrate moisture. Results of the statistical analysis have confirmed that the peat moss moisture is significantly differentiated within the homogeneous production field of the forest seedlings. The study findings suggest that irrigation systems should be adapted to specific situation of substrate moisture at the nursery surfaces aimed at optimised water management.

Keywords: Forest nursery, Scots pine, peat moss substrate, irrigation, water content

1. Introduction

Innovative controlling systems of peat substrate water balance for forestry nurseries have primarily focused on the problems related to water retention, which is important in irrigation management strategies especially for seedling cultivation. Water balance within the production fields in container system determines plants' growth and development, physiological activity, as well as effectiveness of fertigation (Day 1980; McDonald 1984; Prévost et al. 1989; Goodwin et al. 2003; Warsaw 2009; Kargas et al. 2013; Nemali and Iersel 2013).

In container technology, pine seedlings require constant monitoring of peat moisture, because it is one of the most important factors determining their proper growth. The HIKO-120ss cassettes suspended on the racks filled with a small amount of medium-concentrated substrate with high air capacity and low capillary water capacity are exposed to rapid drying. In the initial period of development, the seedlings require frequent spraying to compensate small retention of water with a high demand for it. Unfortunately, forest workers often forget that over time, the substrate parameters change; the leaves have a larger surface area and the substrate is overgrown by the roots. Therefore, the irrigation system timetable should be modified, especially when water resources are limited and the cost of obtaining it is constantly increasing (Heiskanen 1995a,b; Goodwin et al. 2003; Cameron et al. 2004; Veijalainen et al. 2007; Bumgarner et al. 2008; Warsaw 2009; Chappel et al. 2013).

Numerous investigations have been performed to check the physical properties of peat substrates used as a base for the production of forest seedlings in containers. Previous studies have also focused on defining the parameters necessary to effectively describe the air and water status. These parameters are the result of physical influences of the peat composition, container geometry, and the extent of root development. The height of the rack and distance from the edge of the cassettes to the soil are also very important. In this zone, there

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is aeration, and it inhibits the excessive growth of roots. The production of seedlings, though under constant surveillance, requires attention, particularly with respect to water management, which is responsible in maintaining the optimum moisture of the substrate (Campbell et al. 2003; Dumroese et al. 2006; Prehn et al. 2010; Niemali and Iersel 2013; Hoskins et al. 2012; Kargas et al. 2013; Durło et al. 2018).

The different drying rate of the peat substrate in cassettes is another important issue, which is characterised by large variation within the production field and its fragments, and even within the seedlings' cassette. The seedlings located on the edges of the field and in those fragments that are directly exposed to outside radiation near the side shade are the ones that undergo drying quickly. Therefore, investigations on spatial variability of substrate moisture are important. The aim of this research was to evaluate the possibility of using automatic multipoint Modbus RTU monitoring system equipped with the digital moisture sensor to analyse the temporal and spatial volumetric water content in the production fields of pine seedlings (*Pinus sylvestris* L.) produced in the container technology in Poland. An overall conceptual model will be presented to help describe the effects of nursery practices, production field layout, and its orientation on moisture content of containers. The research hypothesis says that peat moisture is significantly differentiated within homogeneous production field of the forest tree seedlings.

2. Materials and Methods

This study was performed in the production fields of Scots pine seedlings (*Pinus sylvestris* L.) produced using the container technology in "Nędza" nursery farm in Rudy Raciborskie Forest District located in southern part of Poland (50.168538° N; 18.317763° E) from May to October 2017 (Figure 1). The primary experiments on substrate moisture were conducted from the middle of May to middle of October in 2017 during initial and main phase of seedlings' development. We designed the monitoring system based on the multichannel electronic recorder MPI-DN (Metronic Corp, PL) equipped with 20 channels for measured process values (transmission rate from 3 s to 60 s), 16 math channels, and 4 relay outputs (Figure 2, 3). Twelve digital moisture probes (HD3910.2) were arranged in equidistant over the production fields including places such as the edges of the field, the interior zone, the extreme edges, and the middle part (Figure 2, 3, 4, Table 1). There were two sensors in one sector. Maximum line length was 125 m. In addition, the one air temperature and humidity transducer was connected to the main unit of data collection system. Every probe was completely submerged in the cells of HIKO V-120ss cassettes. There were about 525 Scots pine seedlings per one square meter (14 HIKO trays / segment) growing on a substrate composed of sphagnum peat moss (95%), perlite (4.4%) dolomite (0.42%) and NPK fertilizer (0.18%) (Table 2, 3). Communication solutions of the multi--channel electronic recorder contain address, function, register, format and ID number associated with the unique port.

Figure 1. Localization of production fields (regional) and research object (black contour) (Source: Google Earth, Imagery date: 2016-08-27, elev. 205 m a.g.l)

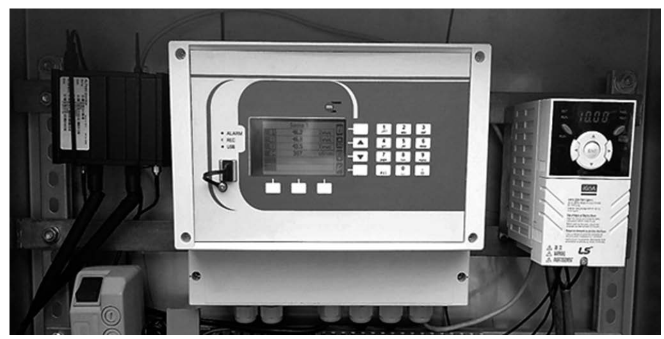

Figure 2. MPI-DN multichannel electronic recorder (middle) network connection router (left) and wave modulator for irrigation system (right) at research field in Nędza nursery farm (photo. G. Durło)

Figure 3. MPI-DN multichannel electronic recorder Modbus RTU(left) T-splitter for RS485 (middle) and HD3910.2 digital moisture probe (right)

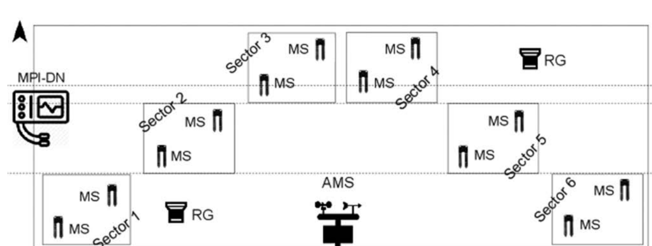

Figure 4. Layout of measuring equipment in the experimental field (MPI-DN – data logger; MS – moisture sensor; AMS – automatic meteorological station, RG- rain gauge)

Table 1. Technical specifications of sensors (type HD-3910.2) for soil volumetric water content

Measuring principle	Capacitive
Measuring range	0…60% VWC (0-100% MPW)
Accuracy (for 23 °C)	3% between 0 and 50% VWC, EC < 5 mS/cm)
Measuring volume	diameter: 40 mm x H=110 mm for the 3-electrode probe
Temperature sensor	NTC 10 k for 25°C
Measuring range/Res/Accuracy	-40…+60°C/ 0.1°C / ± 0.5°C
Power supply/Consumption	5…30 V DC for versions with RS485/ 2 mA 15 mA peak
Output	RS485 with MODBUS-RTU protocol

Table 2. The physical characteristics of a peatmoss substrate in different sectors (averages) on the production field (May 2017)

Zone	Bulk density ($g \cdot cm^{-3}$)	Total porosity (%)	Water capacity (%)	Air capacity (%)	pH
Sector 1	0.98	93.0	74.0	26.0	5.50
Sector 2	0.99	92.0	72.0	28.0	5.40
Sector 3	0.98	93.0	73.0	27.0	5.50
Sector 4	0.10	94.0	72.0	28.0	5.50
Sector 5	0.99	93.0	72.0	28.0	5.40
Sector 6	0.98	92.0	73.0	27.0	5.50

Table 3. The chemical characteristics of a peatmoss substrate in different sectors (concentration %) in the production field (May 2017)

Zone	N (%)	P (%)	K (%)	Mg (%)	Ca (%)
Sector 1	0.7403	0.023203	0.093578	0.3912	0.9711
Sector 2	0.7659	0.023308	0.081303	0.4006	0.9983
Sector 3	0.6973	0.023963	0.100198	0.3891	0.9431
Sector 4	0.7243	0.023405	0.091513	0.3964	0.9755
Sector 5	0.7412	0.023522	0.098856	0.3874	0.9804
Sector 6	0.7183	0.023486	0.099421	0.3958	0.9887

Soil moisture sensors (HD3910.2) measure the volumetric water content of the soil by measuring the dielectric constant of the soil, which is a strong function of water content. However, not all soils have identical electrical properties, especially organic matter. Due to variations in peat moss texture, porosity and salinity, the specific calibration for soil moisture probes results in approximately ± 2–3% accuracy. Prior to this research, each sensor was calibrated for best possible accuracy in volumetric water content measurements. The standard multipoint calibration procedure was used (Sakaki et al. 2008; Kun et al. 2015).

All sensors and probes were operated in Modbus RTU system at 9600 frequencies with a data transmission rate of 60 s. Adjustment of devices consisted of pairing of addresses, while the control of information exchange was by wire signals and was subjected to verification in automatic protocol, every 3 s on average, for the whole day. The front panel of MPI-DN electronic recorder has a full colour graphic TFT LCD monitor with 272 × 480 pixel and with membrane keyboard, which operates between 0 to +50 °C. Storage temperature is from −20 to +80 °C. Table 2 shows technical details of this device.

An initial quality analysis and overall file review were performed in the application. In addition, the program generates daily reports, which facilitates the development of results and allows for rapid analysis of the variability of moisture conditions in the field. Then, the data was segregated and exported to the files in csv format. Further analysis was performed using the Statistica 12.5 software (StatSoft, Inc. 2014). The statistical analysis of data was conducted in two steps. The first step concerned the significance of differences in substrate moisture in particular zones of the production field. The second tested the influence of the cassettes' position on the rate of drying. To verify the research hypothesis, one-way analysis of variance (ANOVA) was performed, and the Tukey's honestly significant difference (HSD) post hoc test was used (Dunn and Clark 1990)

We performed the experiment from the last decade of May till the middle of October 2017; the series were divided into several hours, over a dozen hours, several days, and decades. Such division has given information on which fragments of the field are the moistest, the least moist, and which are relatively stable regardless of atmospheric conditions. This division also allowed the segregation of rain-watering and irrigation periods, and periods where no liquid was present on the field. Scots pine seeds were sown on May 24, and the seedlings obtained the first class of quality at the end of September (PN-R-67025 1999). The study was conducted under natural conditions of seedlings production in accordance with the applicable procedures (Brisette et al. 1991; Mattsson 1996).

Divergence of substrate moisture in Scots pine seedling fields has been observed both in terms of temporal and spatial patterns. Despite the small distance between probes, evenly spaced seedlings, very similar biometric features, and homogeneous peat substrate, results indicate that both the field area ie. The distance from the lateral edge and the distance from the beginning of the field determine the distribution of the examined element.

The automatic weather station was right next to the research field. Using standard observations of weather conditions by 10 minutes interval and then an hourly, daily, weekly and monthly indexes has been calculated. The combined data base consists of 550,800 independent records. Weather conditions during the growing season were close to the multiyear average, only September was more cloudy and rainy. Average seasonal air temperature was 16.3 ºC (st. dev. 5.5 ºC), relative humidity 78.7% (st. dev. 16.5) and total precipitation was 334 mm (Table 4).

3. Results

The mean moisture content of the peat substrate in the Scots pine production field was found to be 41.2% VWC with a deviation of 5.1% in June (min 36.1% – sector 3; max – 45.6% sector 6) and 44.5% VWC with a deviation of 5.32% in September (min 41.1% – sector 4; max 47.8% – sector 6). The differences between the sectors were the highest in June (Δ = 9.6%), the smallest in September (Δ = 6.7%) as a result of weather conditions (Figure 5, Table 5). In the course of the decade, the differences were greater. During dry weather (June), the differences were over 22% VWC, while in the wet weather (September) the differences were much smaller (Figure 6, 7).

Overnight, the average moisture content of the substrate in the field (July) was about 41.5% VWC; it was 40.3% during the day and 41.0% VWC during evening. The rate of substrate shedding was greatest about the outer edge of the field; in this zone, where the potential evapotranspiration is greatest, there is the fastest air flow and highest direct sunlight, which means the highest values of vapour pressure deficit, even

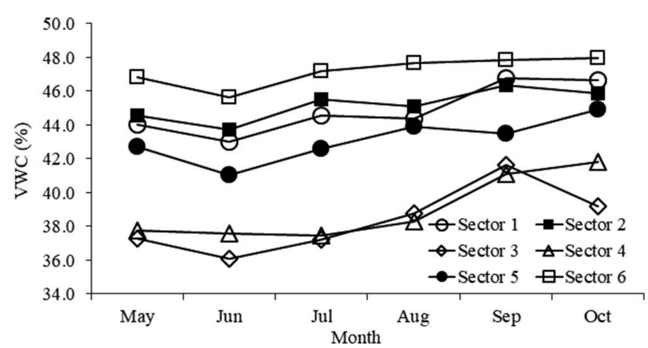

Figure 5. The course of volumetric water content (VWC%) in different sectors at the production field of pine seedlings in Nędza nursery farm (growing season 2017)

Table 4. The monthly indices of weather conditions at the study area (averages/sum) Nędza nursery farm 2017

Month	Air temperature (ºC)	Relative humidity (%)	Vapour pressure deficit (hPa)	Precipitation (mm)	Solar radiation (MJ·m^{2}·d^{-1})	ETP (mm)
May	14.4	77.1	4.12	37.2	336.06	63.8
June	18.7	71.2	6.33	40.4	418.24	77.2
July	19.4	76.5	5.42	70.3	357.33	67.1
August	20.5	76.4	5.72	44.5	299.32	56.7
September	13.8	86.4	2.37	102.7	151.13	29.4
October[1]	11.3	84.7	2.08	38.6	48.78	9.92

above 32.0 hPa (Table 6−8). The mean difference in substrate moisture between the inner and outer part of the field during a normal day with watering was found to be 6.6% VWC between the innermost part of the field. In the extreme external parts of the field, the mean difference in substrate moisture was found to be 9.4% VWC and the difference between the start and the end of the field (shaded) was found to be 2.5%. The highest recorded differences in the same locations were up to 19% in the first case, 22.5% in the second, and 8.5% in the last sunny days without irrigation with vapour pressure deficit above 25 hPa (Table 7).

Analysis of substrate moisture variability at different times of the day indicates that the greatest variation between the sectors occurs in the afternoons at the end of a clear day without precipitation and without sprinkling. The average substrate dry up rate calculated as a change in VWC% moisture varies from 0.52% on the field edge per hour during the day without irrigation to 0.05% VWC in the internal zone

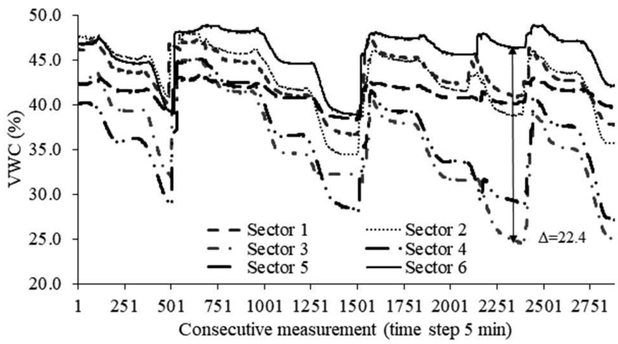

Figure 6. The course of peat moss moisture by various sectors at research field during dry weather, one decade in June 2017 (Δ = 22.4 maximum range)

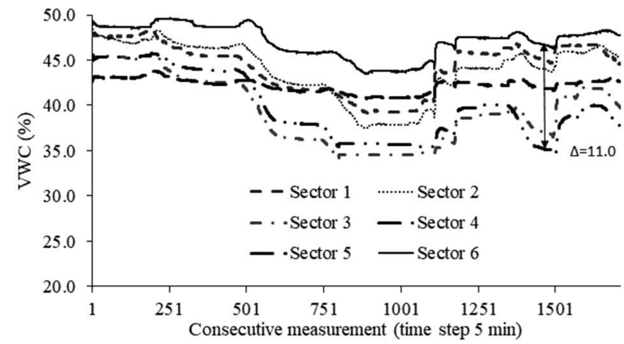

Figure 7. The course of peat moss moisture by various sectors at research field during wet weather, one decade in September 2017 (Δ = 11.0 maximum range)

Table 5. Statistical characteristic of measurement series of peat substrate moisture (VWC%) at the production field of pine seedlings in Nędza nursery farm (June 2017)

Zone	Average (%)	Minimum (%)	Maximum (%)	Stand. Dev. (%)	Range (%)	Coef. of Var. (%)
Sector 1	44.61	35.78	48.64	2.78	12.86	6.23
Sector 2	43.99	31.45	49.36	3.27	17.91	7.43
Sector 3	36.12	19.80	45.55	5.45	25.75	14.30
Sector 4	38.01	19.31	45.88	5.06	26.57	13.31
Sector 5	42.55	38.40	44.08	1.10	5.68	2.59
Sector 6	45.62	38.88	50.63	2.19	11.75	4.67

Table 6. Statistical characteristic of interval series (one-hour) of peat substrate moisture (VWC%) at the production field under irrigation in Nędza nursery farm (July 2017)

Interval	Average (%)	Min (%)	Max (%)	Stand. Dev. (%)	Amplitude (%)	Coef. of Var. (%)
Night	41.46	31.67	46.68	3.78	15.02	9.39
Morning	41.48	31.55	46.32	3.85	14.77	9.56
Noon	40.32	31.15	46.95	3.48	15.81	8.59
Evening	40.99	31.88	46.98	3.65	15.10	9.21
Sunny day	41.02	31.33	45.97	3.94	14.64	9.60
Cloudy day	42.02	31.98	47.59	3.32	15.61	7.90

Table 7. Number of cases with moisture value ranges (one-hour interval) of peat substrate at the production field under irrigation in Nędza nursery farm (August 2017)

Threshold	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6
>49%	2	3	1	1	1	78
41-48%	567	598	200	227	503	599
27-40%	148	116	450	465	208	34
19-26%	2	2	67	27	6	8
<18%	0	0	1	2	0	0

Table 8. Dryness ratio % (from sunrise to sunset) in particular zones of the production field under irrigation in Nędza nursery farm (May - September 2017)

Month	Sectors of production field		
	Inner zone	Middle part	Outer zone
May	0.09 (±0.01)	0.17 (±0.02)	0.29 (±0.03)
June	0.18 (±0.02)	0.21 (±0.03)	0.41 (±0.04)
July	0.23 (±0.03)	0.29 (±0.03)	0.39 (±0.05)
August	0.16 (±0.02)	0.17 (±0.02)	0.19 (±0.02)
September	0.06 (±0.01)	0.09 (±0.01)	0.12 (±0.02)

of field per hour (Figure 8, 9, Table 8). The seasonal average of dryness index was in the range from 0.14% to 0.33%. The results of one-way ANOVA confirm that the peat moisture distribution data was similar to the standard normal model as well as the residuals were normal (Figure 10). Then, the data were tested by the hypothesis that whether the groups' (sectors) variances were equal. Levene's test results showed that this hypothesis was true: MS effect 89435.4 and MS error was 4.415 (F = 20256.9; p < 0.001) (Table 9). The results of frequency analysis of substrate moisture indicate that the outer zone of the production field, beyond the range of the side shade, was clearly different from the others, which confirms that it is particularly susceptible to drying and requires attention during irrigation. The inner edge close to the track shows stability in the area of high humidity (Figure 11). The results of ANOVA and cluster analysis confirmed the earlier hypotheses of field delineation of zones with different physical properties of the peat substrate. It is an important argument in discussing the need to apply irrigation modifications directly on lances.

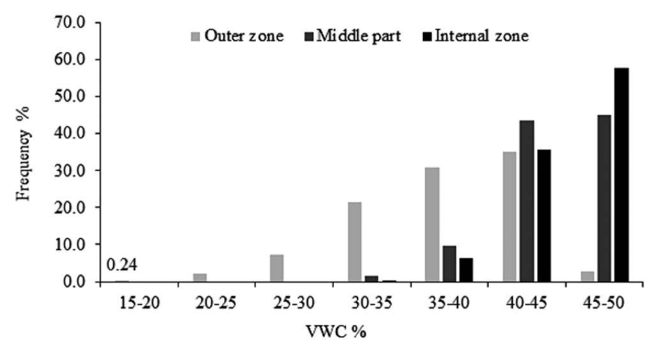

Figure 8. Frequency diagram of substrate moisture (one hour) in particular zones of the production field of pine seedlings under irrigation in Nędza nursery farm (Jun - Sep 2017)

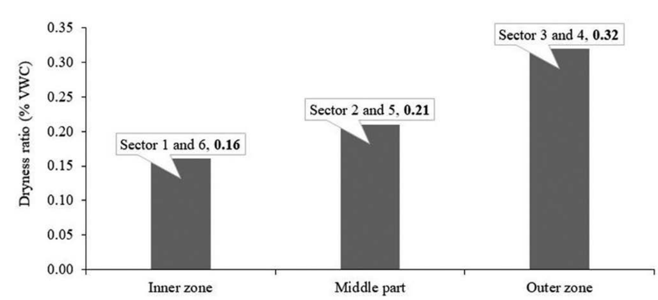

Figure 9. Monthly average of dryness ratio in particular zones of the production field of pine seedlings under irrigation in Nędza nursery farm (May - Sep 2017)

4. Discussion

The temporal variability of the moisture content of the substrate in the Scots pine production field results from several factors such as the evapotranspiration rate, frequency of irrigation, and volume of liquid given per field. In addition, the method of water supplies, size of the water droplet, ramp time, and finally, the surface of the plant assimilation

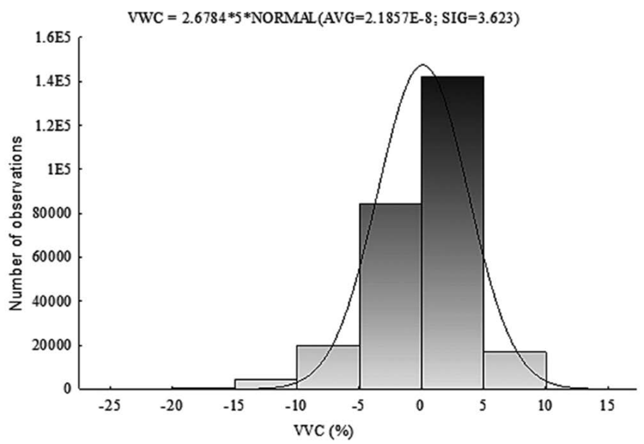

Figure 10. The residuals distribution diagram of peat moisture series in different sectors of production fields in Nędza nursery farm (June - September 2017)

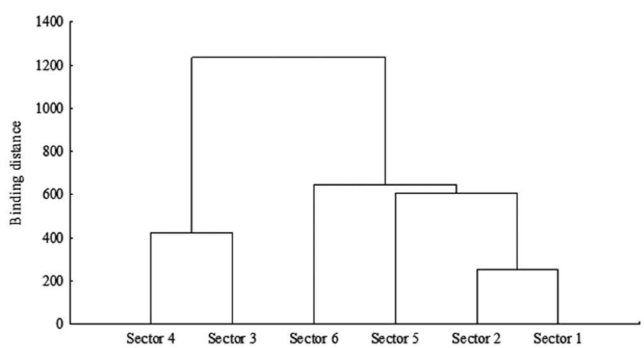

Figure 11. Dendrogram of cluster analysis (L_2) of substrate moisture in sectors of the production field of pine seedlings under irrigation in Nędza nursery farm (June - Sep 2017)

apparatus also play an important role. On the one hand, we have a number of qualitative and quantitative variables and on the other hand, we have the technological capabilities of sprinkler systems and the reliability of service. It turns out that under almost identical conditions (atmosphere, vegetation, and substrate), we get quite a considerable variation in the parameters being tested, although the manufacturers of rainwater sprinklers and fine-droplet nozzles try to ensure the highest reproducibility of their components. Cameron (2004) and Warsaw (2009) point out similar limitations, suggesting that strict adherence to the liquid feed time due to the changing surface of the seedlings is warranted. This aspect is of particular importance for the production of deciduous seedlings, which, in the early stages of development, lighten the substrate relatively quickly, resulting in increased interception (Lamack, Niemiera 1993; Bilderback 2002; Dumrose et al. 2006; Belayneh et al. 2013).

It is also important to take into account the changes in water pressure in distribution systems in nurseries, because in many cases, due to the large number of fields and unequal load during the day, the pressure in the sprinklers can fluctuate by up to several percent. Consequently, the efficiency of the irrigation system can vary depending on the current dispersion of the liquid in the valve.

Assumptions of this study are focused on obtaining as much accurate information as possible about the differentiation of moisture conditions in the production area, primarily to optimize irrigation and regulate the stock of water in the substrate, depending on the current demand of plants for moisture. The solution proved to be effective and efficient. Similar results were obtained in other studies on container nurseries (Scoggins 2006; Treder 2007; Million, Yeager 2012; Kargas et al. 2013). These studies have played an important role in optimising irrigation systems and improving the quality of stocked nursery produce. The technique of multipoint sensing provides a simple, precise, and non-destructive way to obtain information about physical features of peat substrate. Multichannel electronic recorder with Modbus RTU connection sensor network have a very good resolution, fast acquisition, and great flexibility. But it should be emphasised that the large variation of the examined elements within the field indicates that the number of probes should be increased to 1 piece per 2–3 are and their distribution should take into account the directions of solar radiation, the type of side shade, and the current state of the assimilation apparatus. For example, in the production areas of 100 m^2, four probes should be spread along the long side at a distance of up to 40 cm from the edge, the rest in the field, and one at the beginning and the end. Such an arrangement will provide sufficient information on current field conditions, and will, however, be an important aid in modifying current watering plans and optimising water consumption during production.

In order to provide the right conditions for the plants to grow by keeping the substrate moisture at the optimum level, we must remember that the production of the substrate is changing dynamically in a short period of time. Under very unfavourable weather conditions (excessive insolation, wind), there may be a significant reduction in substrate humidity which requires the intervention of persons supervising the breeding. The use of modified sprinklers with the possibility of smooth regulation of the dump zone is an important element of the water management strategy at the container nurseries.

5. Conclusion

The monitoring of peat-moss substrate moisture is essential to successfully manage the irrigation of containerised seedlings produced in forest nurseries and will lead to a more rational use of water, fertilizers, and pesticides and to improved protection of groundwater. On the basis of the measurement data and analysis, the following conclusions can be drawn:

1. The average moisture of the peat substrate in the Scots pine production field with a normal irrigation schedule was found to be 41.4% VWC with a 5.1% deviation and ranged between 25 and 45% VWC depending on the weather conditions and irrigation schedule.

2. The average difference of VWC% of peat substrate in Scots pine production field between sectors was found to be between 6.5% and 9.5%, depending on the location of the cassettes.

3. The highest amplitude of substrate moisture was observed in the sector adjacent to the outer edge of the field from the side of the road; the difference between the extreme values was found to be 24% during the day, 15.6% during the decade, and 8.5% during the month.

4. The most stable moisture conditions were observed in the inner zone of the field, in its upper range (eastern), due to the side cover of the stand and the proximity of the second production area. The variance in this zone was found to be 9.5% during the day, 5.2% over the decade, and 2.4% in the month.

5. The recommended number of probes for measuring substrate moisture in the Scots pine production fields is 1 unit per 2.5 are, so that good interpolation procedure evaluation results are obtained.

6. The fastest rate of substrate shedding of 0.5% VWC per hour was observed at the edge of the field during a clear day with vapor deficit above 30 hPa.

Conflict of inte est

The Authors declare no conflict of interest.

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Authors' contribution

G.D. – research concept, assumptions, methods, data comparison, analysis, writing; M.K. – results interpretation, preparation and text editing, language correction, research organization, data verification, review of bibliography; S.M. – language correction, review of bibliography; J.B. – language correction, review of bibliography.