Int. j. adv. multidisc. res. stud. 2023; 3(5):102-107

Received: 14-07-2023
Accepted: 24-08-2023

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

High-Resolution Soil Moisture Measurements in Rational Fertilization and Irrigation Methods as Part of the Sustainable use and Management of Soil Under Climate Change - DIY Solutions

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Abstract

Current climate changes, including drought, represent one of the most severe and extreme natural phenomena, directly affecting the environment, economy and society, and increasingly leading to soil degradation. In drought-stricken areas, losses in agricultural production are driving up food prices. The world's demand for water will continue to grow further in the coming decades. In view of the presented facts, there is a tremendous need for a systemic approach to saving water in the process of soil reclamation and conducting multidisciplinary research in this field. The problem of fertilization is linked to reasonable irrigation. These processes ought to be synchronized and run simultaneously, under the control by the system. This paper presents a prototype measurement probe as an element of a measurement network and the results of tests of its application in under use. The purpose of this research was testing a cheap DIY to solution identify the availability of water resources in the soil layer where the major plant root mass is found, i.e., to a depth of up to 110 cm, and to rationalize the management and improve the efficiency of water use during irrigation, as well as to monitor the migration of water in the soil in the era of climate change. The conducted tests have yielded concrete conclusions - current climate change is already resulting in unusual situations, including the different behaviour of water migrating through the soil. Considering that a wide variety of soils and geological systems are present, it is extremely important to understand these mechanisms in great detail, which makes the created solution feasible. Such a detailed analysis of water migration in soil under use can very successfully support, for example, a low-cost precision irrigation (preventing drought), or fertilization, indicating periods when and where to introduce nutrients after rainfall so that they naturally reach the depth of the largest root mass as quickly as possible. The DIY solution can be crucial in Third World countries by conducting at least single, cheap soil moisture measurements, and in many other places affected by the problem of water deficit, it can be an alternative to extend existing monitoring systems.

Keywords: High-Resolution Soil Moisture Measurements, Fertilization, Irrigation, Sustainable Use and Management of Soil, Soil Moisture Measuring Probe, DIY Solutions

Introduction

Soil may lose its properties as a result of intensive cultivation, excessive use of mineral fertilizers, deterioration of the environment, as well as industrial activities (Sheshma *et al*. 2018; Shabanpour *et al*. 2019) [20, 19]. The processes of soil reclamation have been known since the 1920s. Land reclamation (restoration) is the process of giving or restoring degraded and devastated land its original use and natural values. Some factors are beyond human control. On the current state of climate change, drought is one of the most severe and extreme natural phenomena, having a direct impact on the environment, the economy and society, gradually increasingly leading to soil degradation. However, certain measures have the potential to slow or even prevent soil degradation. For this purpose, fertilization and irrigation treatments of agricultural land are being conducted (FAO 2021; Masundaram *et al*. 2021) [7, 13]. These tend to be costly processes, raising the price of agricultural products, which, in the event of outbreaks of armed conflict and economic crisis, might lead to deepening poverty in societies. In drought-stricken areas, losses in agricultural production result in food prices increase that affects everybody (FAO 2022) [6]. This applies to both plant and animal production. Less water also means less availability of feed, which is of inferior quality as a result of drought. High temperatures reduce animal comfort, which, for example, in the case of cattle, results in a decline in the volume of milk and meat production (Summer *et al*. 2019; Miller *et al*. 2022) [23, 14]. Prices of consumer goods in 2019-2022 rose mainly due to food being more expensive (OECD 2022) [17]. Since 2022, this has been compounded by the war in

Ukraine (Barker 2022) [1]. The persistence of adverse weather conditions, combined with rising prices of agricultural raw materials on world markets, reduces the likelihood of a scenario of falling food prices that could cushion the increase in the prices of other products (Batten *et al*. 2020) [2]. The European Centre for Medium-Range Weather Forecasts research estimates that Europe's water deficit will continue to worsen until 2100. Utilizing climate models and socioeconomic scenarios, the World Resources Institute analysed the rate of surface water depletion in 167 countries by 2040. The analysis resulted in 33 of them being singled out for extreme stress on water resources, and thus extreme water scarcity. 14 of these countries are located in the Middle East, but European countries also appear in the prediction. Areas on the Iberian Peninsula and in Central Europe may suffer the most during this time. Per capita levels of freshwater resources are already alarmingly low in the EU's most populous member states - France, Spain, Germany, Poland, and Italy. It is less than 3,000 cubic meters per capita, while a deficit can be mentioned when the rate reaches 1,700 cubic meters per capita. Such a critical condition has been registered by the Union in Malta in recent years, as well as in Cyprus, the Czech Republic and Poland (ECMWF 2022) [5].

Global demand for water is projected to increase even more in the upcoming several decades (Nigam and Rahi 2016) [16]. This will be driven not only by global population growth, but also by increased consumption and migration of rural residents to cities, whose resources will be further strained (Kurek *et al*. 2019; Gu *et al*. 2021; Lowe 2022) [11, 8, 12]. The United Nations (UN) is estimating that the world's population will grow to 9.3 billion by 2050, with 6.3 billion people living in urban areas (nearly half as many as in 2011).

In view of the facts presented, there is a great need for a more systemic approach to water economy. With rational irrigation comes the problem of fertilization. Both of these processes should be synchronized and take place simultaneously, under the control of the system (if technically and biochemically possible).

In this paper, a prototype measurement probe that is part of a measurement network is being presented, as well as the results of testing its application in soil remediation. The project is based on the Do It Yourself (DIY) concept. This term is associated with independent execution of devices - without the involvement of professionals and huge financial resources, also with a non-commercial and free of charge approach. The solution enables the extension of techniques used in precise agriculture particularly for restoring and maintaining soil condition. To date, no one has attempted to study and analyse the problems at hand on a larger scale, in a way that ensures the acquisition of high-resolution data.

Materials and methods

In many countries, including Poland, the type of agricultural drought is monitored by governmental units (e.g., Institute of Soil Science and Plant Cultivation – State Research Institute, https://en.iung.pl/). However, there are only 18 field measurement points nationwide, and the cost of a single soil moisture profile probe at such a point exceeds the amount of several thousand euros. Monitoring is also carried out for entire countries, but this research is based only on satellite data from EUMETSAT H-SAF (European Organisation for the Exploitation of Meteorological Satellites, Operational Hydrology and Water Management) for two layers: 7-28 cm and 28-100 cm (in this case, costs are from a minimum of 30,000 EUR (PocketQube) to a maximum of several million EUR). However, first, the satellite data is not completely real, as it comes partly from mathematical modelling (interpolation in a 25 km grid). Secondly, the calculated humidity indicators do not help individual farms due to their low spatial resolution, as they do not take into account local conditions. Meteorological monitoring is carried out simultaneously and independently, but it does not include soil parameters.

The presented prototype of a probe and a network of probes for measuring the amount of soil water content and precipitation and monitoring drought has been designed in a way that guarantees maximum simplicity, minimum costs (50 ± 10 EUR / probe - this is only the cost of the components and the devise has to be manufactured by the potential user), short production time and high repeatability (Fig 1). Technical details, including construction and code used, have been presented in supporting materials (Juśkiewicz 2022) [10]. Such an approach may contribute to the popularization of this technical solution, facilitating research and eliminating many emerging problems (Brauer 2022) [4]. The use of mass-produced products is both beneficial and disadvantageous. On the one hand, mass production does not guarantee high quality, on the other hand, the huge repeatability and the use of hundreds of devices for the price of one commercial device allow for the collection of high-resolution data that can meet the requirements of Big Data times. This is an advantage that, until now, could not even be taken into account.

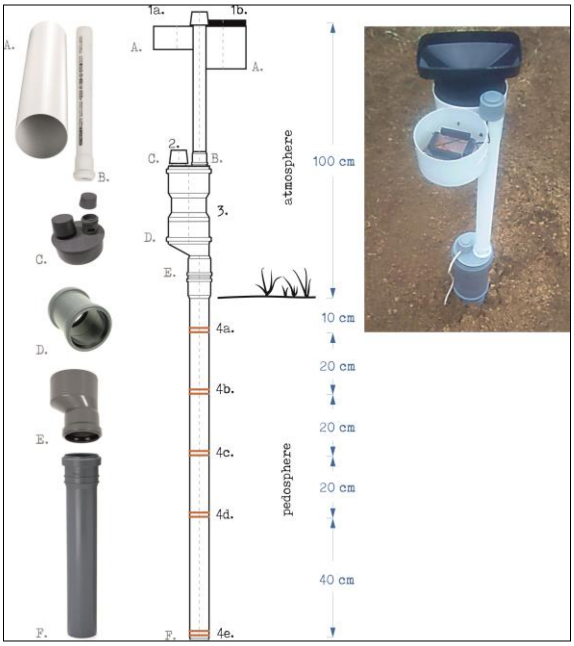

Fig 1: Proprietary measuring probe - element of the measuring network. Diagram of the proprietary casing, the basic element of the rainfall and drought monitoring system: sensors for measuring the duration and intensity of rain (1a) and the amount of rain (1b), sensors for measuring air temperature and humidity (2), data collection, processing and transmission system – Arduino and Raspberry Pi (3), soil moisture sensors at the depths of 10 cm (4a), 30 cm (4b), 50 cm (4c), 70 cm (4d), 110 cm (4e) and the materials used: PVC pipe DN 150 (A), PVC DN 32 (B), PVC ventilator DN 110 (C), PVC sleeve DN 110 (D), PVC reduction DN 110/75 (E), PVC pipe DN 110 closed with a cap (F). Own source (Juśkiewicz 2022) [10]

The aim of the research was to test the proposed solution by determining the availability of water resources in the soil layer with the highest plant root mass, i.e., to a depth of 110 cm, in order to rationalize management and improve water use efficiency during irrigation, and to monitor the movement of water in the ground in the era of climate change.

Two questions were asked: 1) Can DIY project high-resolution soil moisture testing help combat drought by supporting irrigation? 2) Is there a possibility of low-cost fertilization of plants with the participation of natural processes of rainwater infiltration?

Study area

In order to answer the questions posed, a measuring probe was designed and constructed, and field studies were carried out in Central Europe (Poland, Kuyavia region) in an area highly prone to water deficit (Fig 2). Measurements were carried out in the area of the Ciechocinek Lowlands in the Kuyavia region, formed over the last 20,000 years by the Vistula River. It consists of floodplain terraces built of sand, clay sands, including mud, and the moraine plateau adjacent to it from the south, consisting of various types of clay. The most typical sediment is river mud - up to a depth of 35 cm in the soil profile (with a lot of fine grains), sandy and loose on the surface up to 10 cm. From 35 cm to about 95 cm, it contains medium-grained, well-washed sand, under which there is iron sand with an admixture of fine-grained silt (it is a compact sediment).

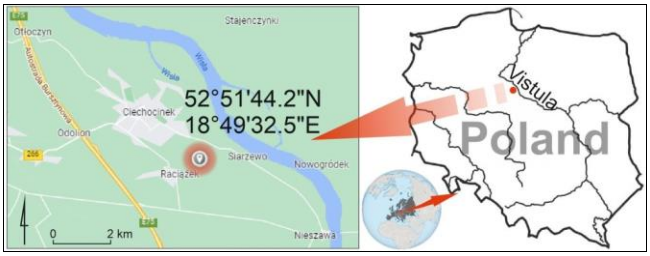

Fig 2: Location of study area

Soil moisture detection - methodology of the experiment

The intervals between the individual detectors were adopted on the basis of studies of the root mass of crops, based on studies in which the lengths of the root systems of field crops were compiled. Determining the moisture content at these specific depths is extremely important as a well-hydrated plant makes better use of the nutrients from the soil. For example: in the 0-10 cm layer, more than 51% of the root system weight of spring wheat develops; in the range of 0-30 cm over 90% of winter wheat, the same is true for spring and winter barley and oats. The main root mass of the maize is located at a depth of up to 70 cm; Usually up to 30 cm in the topsoil, potatoes take up nutrients - their root system is not deep. At a depth of 30–100 cm in the arable layer, sugar beet produces a storage root with a few sorbing roots, the main mass of which is produced in the subsoil. Winter oilseed rape produces a deep root system, and the tap root is slightly more than 110 cm. In the case of legumes, for example, horse bean has a strongly developed tap root system up to 110 cm long, and its lateral roots do not exceed 50 cm. Similarly, peas produce a tap root system, thin, with a large number of lateral roots. The length of the main root is 110 cm, and the lateral roots are distributed within 50–70 cm. In the case of forage alfalfa with the root system reaching even more than 12 m into the soil, which is an exceptional situation, over 85% of the root mass is in the 0-30 cm layer. Control at these specific depths is key to rational irrigation and fertilization.

Soil moisture sensors have been calibrated to give absolute results in percent. Calibration was performed using the weight method. The weight of moist soil samples was determined as well as the weight after 3 hours at 105 ° C. The difference made it possible to determine the correction factor and, as a result, the actual result of soil moisture. All sensors were validated using certified devices.

Results and discussion

Determining the needs of irrigation

For many years, the method most commonly used by farmers in practice to determine irrigation needs has remained the one based on a tactile assessment of the soil's moisture status, or a visual determination of the plant's condition. Thus, the agriculturist is capable of making only a very approximate assessment, on the basis from his own experience, on when to irrigate the soil. The agriculturalist's decision on how often and how much to irrigate is usually based on a general prediction of soil saturation with water, i.e., irrigating the soil to its full water capacity, the achievement of which is manifested by the appearance of stagnant water on the soil surface. This method is found to be misleading. Often, after a dry period, rainfall dampens only the top section of the arable-humus horizon, so an assessment of the moisture content of the soil surface may suggest an abundance of water, while a few cm below the dampened layer the soil profile is not saturated (Wang *et al.* 2018) [24] (Fig 3). On the other hand, watering the crop until the soil is saturated is both uneconomical and detrimental to the environment. Water from saturated soil will usually drain within one day to a moisture content equivalent to the field water capacity. The agriculturist is then losing all this excess water volume along with easily soluble potassium and nitrogen fertilizers, which find their way into the groundwater, eventually contaminating it (Muhsin *et al.* 2021) [15]. Disappointingly, most of the hydration systems installed nowadays do not allow precision irrigation. Therefore, it is easy for excessive, unreasonable water consumption. At that point, excess water percolates unproductively deep into the soil, leaching the nutrients necessary for plants (Rashimi *et al.* 2017) [18]. Such irrigation disrupts the natural circulation of surface and groundwater (Bouwer 1987) [3].

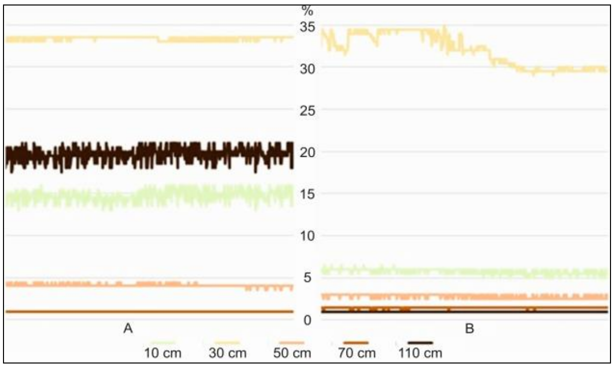

Fig 3: The availability of water at various soil depths with a different proportion of dust and clay particles. A - dusty soil, B - sandy soil. Own source

The amount of available water in soil is described by three characteristic points (levels) of moisture (https://www.fao.org/):

- Permanent Wilt Point (PWP);
- Field Water Capacity (FWC);
- Full Water Saturation (FWS).

The relationship between the most important levels is presented in the formula:

FWC - PWP = WAP (water available to plants)

Each soil formation (e.g., sand, clay, dust or loam) has its own characteristic of the system of moisture thresholds (Fig 4). As can be seen, a moisture content of 15% in the case of sand means half the water capacity, and in the case of clays it is below the permanent wilting point. Precise irrigation is a precise determination of the date and dose of irrigation, but because these doses most strongly depend on the grain size (species) of soil, the most important thing is good soil identification in a given farm, determination of irrigation zones and spatial differentiation of doses (Jobbágy *et al*. 2011) [9].

Under Polish conditions, there are many post-glacial areas with a mosaic of soils, where it is not uncommon to encounter extreme soil quality classes within a single field. Zoning for irrigation is also useful in determining zones for fertilization and crop rotations (Sorensen *et al*. 2021) [21]. Farmers' use of the aforementioned sight-and-touch method wastes a lot of water, energy and time, and very often lowers yields. Irrigate only as needed according to reliable criteria. In practice, we can use climatic criteria (we estimate water needs based on measured meteorological data) or soil criteria (we irrigate based on soil moisture measurements) (Srinivasarao *et al*. 2020; Yadav *et al*. 2021) [22, 25]. Such criteria were used during the study and in developing the probe and measurement network.

During the spring-summer season (May-August) in 2021, research were conducted for 16 points. The research covered soils characteristic of the Ciechocinek Lowland area (sand, sandy loam, including silt) and the moraine upland adjacent to it from the south (various types of clays). In all cases, the average results appeared to coincide with United States Department for Agriculture data for this type of sediment. However, for the summer measurements, there were clear declines that lowered the average values. Measurements in July and August were particularly strongly affected by the drought, when minimum values exceeded the point of permanent wilting. Thanks to the work of the probe, the dose of water needed for irrigation could be precisely delivered to the plants at a specific place and time, and when the soil moisture reached the set value, irrigation was terminated (Fig 4).

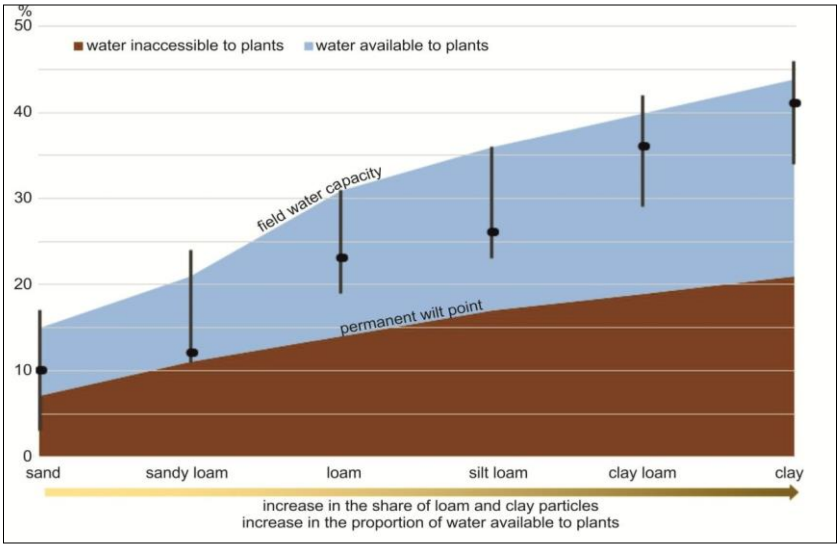

Fig 4: Measured values of water available to plants in various soils against the background of US Department of Agriculture (USDA) multi-year values, brown and blue fields - perennial, black line - range of measured values, black point - mean of measured values. Own source

Case study

After more intensive snowfall, in late December 2021 and early January 2022, the ground was also fairly well irrigated after the snowmelt due to three hurricanes (Arwen, Barra and Corrie) that brought precipitation. The situation was changing in a way that is unusual for this time of year. Further, from February 15, 2022, storms with strong winds and precipitation arrived over Poland.

On February 16-17, 2022, hurricane Dudley appeared, followed by hurricane Eunice on February 18-19, 2022. After them, two more hurricanes (Franklin - February 21 and Gladys - February 23) passed through the Polish area bringing rain. The next 10 days were a rain-free period.

The unprecedented precipitation associated with these events made it possible to draw specific conclusions from the superimposed phenomena of driving rain typical of summer and the slow spring irrigation associated with snowmelt. The most obvious changes are seen in the dry, sandy layer up to 10 cm deep. It reacts the fastest. After an intense rainfall, there is an increase in moisture content from a few % to more than 15% within a few hours. A drop in soil moisture occurs just as quickly. After about 10 hours, after the rainfall stops, the moisture content drops to more than 10%. In the soil layer up to 35 cm, the original moisture content, before the rainfall, was already at more than 30%, so the changes in moisture content are only a few percent and do not increase further. The well-permeable sands below show virtually no change in moisture content. However, the constant infiltration of water through them is evidenced by the fact that the lowest layer at a depth of 110 cm linearly increases its moisture content from 15% to 25% throughout the period, this is the result of a slow increase in the water abundance of this layer. After the end of precipitation, the moist layers, containing fine particles that support water retention, respond quickly to any changes. There are responses after just a few hours, but soil moisture remains relatively constant. In this case, there is a different response at a depth of 110 cm - the changes are more pronounced and need about 2 days for the moisture content to drop (Fig 5).

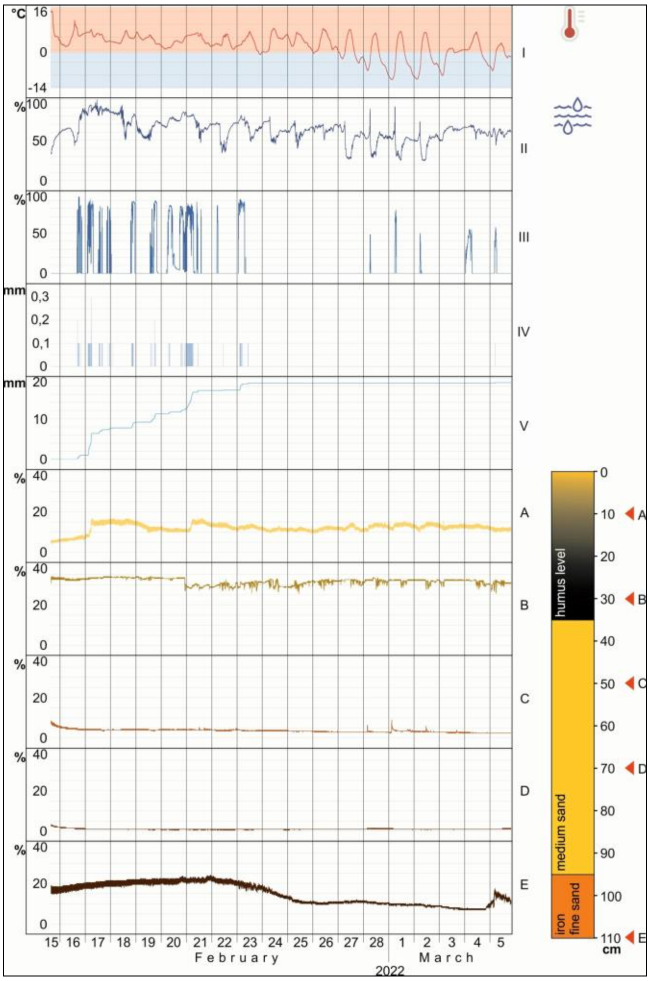

Fig 5: Graphical presentation of measurements of air temperature, air humidity, amount of precipitation, intensity of precipitation and soil moisture from February 15, 2022 to March 5, 2022 in relation to the soil profile. Legend: I - air temperature, II - air humidity, III - intensity of precipitation, IV - precipitation intervals of 45 sec, V - accumulation of precipitation, A - E - soil humidity Own source

Conclusions

Current climate change is already causing unusual situations, including the different behaviour of water migrating in the soil. Given that there is a wide variety of soils and geological systems, it is extremely important to understand these mechanisms in great detail.

The tests of the constructed probe and network as well as the conducted research confirmed that it is possible to: 1) reflect the humidity conditions in great detail, which allow to track the water crisis in real time and effectively support preventive measures in the fight against drought, among others low-cost precision irrigation 2) determine the inertia time of soil reacting to rainfall - thus, introduce fertilizers in crops in a precise manner, adapted to the intensity of rainfall and the type of soil. In the future, soil moisture regimes determined by the operation of large-scale networks can be used as an effective tool for soil rehabilitation planning with minimal investment in time and money 3) the DIY solution can effectively compete with professional monitoring systems thanks to low costs, common access to materials and devices, and obtaining comparable measurement result.

Acknowledgments

The author appreciates comments from anonymous Reviewers and Editors, which improved the manuscript.

Disclosure statement

No potential conflict of interest was reported by the author.

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