REVIEW

on a doctoral dissertation submitted for the award of the educational and scientific degree of "**Doctor**" in: Field of Higher Education 6.1. Agricultural Sciences and Veterinary Medicine, Professional Field: Crop Science, Scientific Specialty "Forage Production, Grassland Management"

Author of the doctoral dissertation: Ivelin Dimitrov Markov – Full-time PhD student at the Department of Crop Science, Agricultural University, Plovdiv

Title of the doctoral dissertation: "Investigate the impact of different sustainable turf management practices on soil C sequestration on intensively maintained sand-based putting greens and how their implementation affects the annual carbon budget"

Reviewer: Assoc. Prof. Dr. Emil Stoychev Vasilev, Maize Research Institute – Knezha, Agricultural Academy, Field of Higher Education 6.1. Agricultural Sciences and Veterinary Medicine, Professional Field: Crop Science, Scientific Specialty "Forage Production, Grassland Management" and "Selection and Seed production of the Cultivated Plants", appointed as a member of the Scientific Juree by order No. RD-16-209/02.02.2026 of the Rector of the Agricultural University.

1. Brief Presentation of the Candidate.

Ivelin Dimitrov Markov was born on 25 March 1982 in Varna, Bulgaria. He completed his higher education at the Technical University of Varna: 2001–2005 – Bachelor's degree in Engineering in Automation, Information and Control Computer Systems; 2014–2016 – Master's degree in Engineering in Automation – Programming of Siemens PLCs.

During the period 2006–2008, he obtained a qualification in Golf Course Design and Construction at the University of Guelph, Canada. From 2009 to 2018, he worked as a Product Manager – Irrigation Agriculture and Golf Equipment at Megatron EAD, Sofia. Between 2018 and 2023, he served as Team Manager at BlackSeaRama AD, Balchik.

In 2019, he completed the course Elements of AI – Artificial Intelligence and Machine Learning at the University of Helsinki. In the periods 2019–2021 and 2021–2023, he obtained an HNC (Higher National Certificate) qualification in Golf Course Management at SRUC – Scotland's Rural College. In 2020–2021, he also completed online certifications in Digital Marketing and Data Science.

During 2023–2025, he undertook an internship related to PhD studies at Tianjin Agricultural University. In 2022, he enrolled as a full-time PhD student at the Agricultural University – Plovdiv, in the Department of Crop Science, within the field of higher education 6.1. Agricultural Sciences and Veterinary Medicine, professional field Crop Production, scientific specialty Forage Production and Grassland Management, for a period of three years. Associate Professor Dr. Atanas Sevov was appointed as his academic supervisor.

At the beginning of 2026, he was released from the doctoral program with the right to defend his dissertation, effective from 28 January (Order No. RD-26-22/02.02.2026 issued by the Rector of the Agricultural University).

Ivelin Markov has excellent written and spoken English skills, extensive experience as a team manager, and valuable social competencies gained through numerous professional trips and training programs abroad.

2. Relevance of the Problem.

The problem addressed in the dissertation is of exceptionally high scientific and practical value and aligns with the challenges of sustainable management of turfgrass communities under changing climatic conditions.

The study tackles a novel, significant issue related to the intensive maintenance and use of golf greens on sand-based soils. In these areas, it is crucial to develop a system of operations that ensures optimal conditions for the growth and development of perennial turfgrass species in accordance with high technical requirements. The sand-based construction of a golf green provides a smooth surface with uniform density and achieves essential characteristics necessary for ball movement. Within this sandy environment, high-density perennial turfgrass (number of plants per unit area) and extremely frequent and very low mowing constitute another core living element of a golf green. These two main components – the sand base and perennial turfgrass under proper maintenance – fulfill the technical requirements of a golf green surface.

Establishing a system for sustainable management of the perennial turf, with a focus on carbon sequestration in the sand base and its annual exchange, is an important ecological issue, and the present study proposes a solution.

The research addresses practical issues related to efficient use of water and mineral fertilizers under seasonal and climatic variations to develop an optimized maintenance regime aligned with natural carbon cycles. Particularly relevant is the integrative approach combining classical agronomic measurements with remote sensing to determine threshold values of key indicators (Bayesian networks) for informed maintenance decisions. This approach aligns with contemporary trends in introducing digital technologies and artificial intelligence for precision turf management.

The topic is also significant for the sustainable management of organic matter and carbon in the sand profiles of golf greens, which have limited capacity to retain water and nutrients. The developed system for managing soil moisture and nitrogen based on threshold levels enables efficient utilization, reducing losses and enhancing the ecological sustainability of intensively managed turf systems.

In this sense, the dissertation addresses current scientific and practical directions in turf management for sustainable maintenance, with results potentially applicable not only in Bulgaria but also internationally.

3. Aim, Objectives, Hypotheses, and Methods of Research.

The aim is to integrate experimental data obtained via remote methods to develop systemic solutions under constantly changing environmental conditions, encompassing the above- and below-ground state of the perennial turf, water and nutrient regimes, and carbon balance to manage the technical condition of golf greens.

To achieve this aim, the dissertation formulates the following key objectives:

- Analyze the effect of different irrigation and nitrogen fertilization regimes on the growth and development of perennial turfgrass on sand-based golf greens.
- Assess root system dynamics and its relation to water and nutrient regimes.
- Investigate changes in carbon stocks and the potential for carbon sequestration in the sand profile of golf greens.

- Apply remote sensing methods (vegetation indices, sensor data) to monitor the physiological state of turfgrass:
    - Use spectral measurements to determine turf density, vitality, and photosynthetic activity.
    - Forecast and make decisions for optimized turf maintenance using artificial intelligence based on probabilities of environmental changes.
- Evaluate the resilience of the maintenance system under different management scenarios.

The dissertation is presented in five interconnected parts addressing systemic sustainable management of intensively maintained sand-based golf greens based on input data for an integrated SMART decision-support system (DSS).

- **Part 1: Optimization of Nitrogen Fertilization.** Nitrogen demand is determined by the growth potential (GP) of perennial turfgrass considering temperature conditions, estimated vegetation index (VI), and variable stress factors to plan daily to weekly fertilization regimes according to DSS.
- **Part 2: Optimization of Irrigation.** Scheduled irrigation is compared with ET-based regimes, considering water uniformity (DU), volumetric water content (VWC) of the turf layer, and water use efficiency (WUE). Threshold values are established for irrigation planning in line with DSS.
- **Part 3: Root System Development.** Quantitative modeling links root growth with environmental conditions under DSS management, including irrigation scenarios, to establish predictive values for root growth and inform fertilization and irrigation decisions.
- **Part 4: Vegetation Index (VI) and Remote Sensing.** VIs are determined based on fertilization, irrigation, in-situ root development, mowing frequency, and turf height. A digital visual model (UNet) was developed to determine the state of golf green components for precision decision-making.
- **Part 5: Artificial Intelligence Based on Bayesian Networks (BN-DSS).** Parts 1–4 are integrated into a modular Bayesian network supporting DSS. Probabilities of minimum values of specific indicators are calculated, and AI (SHAP) forecasts future turf conditions, recommending operations to maintain turf quality and enhance surface carbon sequestration.

The methodological workflow focuses on carbon capture and annual exchange in the sand-turf surface layer of intensively maintained golf greens with four secondary objectives:

- Optimize nitrogen fertilization.
- Optimize irrigation rates.
- Monitor perennial turf root development.
- Remote sensing of vegetation indices (VIs).

- Determine DSS operations to optimize nitrogen, irrigation, and carbon capture in the surface layer.

Research was conducted on two sites with respective climatic conditions: one in Europe (Bulgaria) and one in Asia (China) at relatively similar latitudes. The observational research method used on these sites replicates golf course conditions. Both sites used perennial creeping bentgrass (*Agrostis stolonifera* L.) under specific maintenance regimes and threshold-based operations for fertilization, irrigation, and turf management. Differences in surface layer characteristics, relief, and maintenance history were considered, allowing the development of universal management approaches based on Bayesian networks and AI.

Three groups of indicators were monitored:

- Meteorological and transpiration parameters
- Nitrogen, phosphorus, and potassium content in the root-inhabited sand layer
- Turf condition

These indicators were methodically monitored with modern instruments and fully meet the research objectives. Data from both sites are original and used to inform management regimes across different seasons and stress conditions.

4. Visualization and Presentation of Results.

The results are presented clearly, systematically, and logically, facilitating understanding, evaluation, and interpretation. The author uses a combination of tables, graphs, and figures to illustrate the data, supporting objective interpretation of established relationships and dependencies.

- 43 tables are well-organized and mostly include essential statistical indicators for evaluating result reliability. They allow comparisons between management scenarios (irrigation, fertilization, and decisions) across time and experimental conditions.
- 94 figures are purposefully selected, illustrating changes in key indicators such as turf growth, water and nitrogen availability, and carbon content. Figures reveal trends not easily seen in tables alone, strengthening the conclusions.

The use of remote methods and modeling for visualization demonstrates the applicability of contemporary approaches. Results based on probability calculations and AI allow predictability of monitored indicators.

Note: In Tables 4 and 9 and Figures 19 and 20, abbreviations are not defined. The dissertation should be understandable without referencing additional appendices.

5. Discussion of Results and Literature Used.

The dissertation includes a large number of indicators, all of which fully serve the objectives set in the study. The obtained results have been purposefully and effectively applied to determine the current state of the turf and the surface sand layer. By establishing threshold values for individual indicators within the Bayesian network using Artificial Intelligence, predictive states are achieved, which immediately update the System Maintenance Decisions (DSS) for the course. It should be noted that this updating process depends on constantly changing parameters due to meteorological conditions from early spring to mid-autumn and affects other elements of the golf course, such as the turf and the surface sand layer. This approach has been applied to every part of the dissertation, specifically for optimizing nitrogen fertilization, irrigation, turf growth and development, and the formulation of System Maintenance Decisions.

The results of the individual indicators are discussed in depth and in close connection with contemporary scientific achievements in the field of sustainable management and use of water and nutrient resources in perennial grass communities, as well as carbon sequestration in the surface layer. The author skillfully compares his own experimental data with previously published results from other researchers outside Bulgaria, allowing for a correct interpretation of the observed relationships and placing the results in a broader scientific context.

The discussion is logically structured, with causal relationships sought for each key result, and a critical analysis of the possible mechanisms underlying the observed effects is provided. Particular attention is given to the relationship between irrigation and nitrogen fertilization regimes, the development of the root system, and the dynamics of carbon stocks, with results examined from both physiological and ecological perspectives. This contributes to a deeper understanding of the functioning of turf on sand-based surfaces and the role of management practices in ensuring its sustainability.

A positive aspect of the author is the acknowledgment of the limited number of study sites and the diversity of experimental conditions, which demonstrates a critical approach to the results, reflecting an understanding of the complexity of the studied processes, their interactions, and their impact on the condition of the golf course. This indicates a rigorous research approach and objectivity in drawing conclusions.

The literature used is contemporary and extensive. Sources were carefully selected for relevance to the research topic, including a significant number of peer-reviewed scientific publications, international sources, and authoritative monographs. These references reflect the current state of knowledge on the problem and provide a solid theoretical and methodological foundation for the dissertation. The majority of cited sources are incorporated into the literature review, demonstrating the author's thorough awareness of both established findings and emerging directions in the field.

Considering the nature of the scientific problem and the two specific study sites, the author references a substantial number of sources when discussing the results. Thus, the work presented in the dissertation is well-grounded, and the conclusions drawn carry high scientific value.

6. Contributions of the Dissertation

Scientific Contributions:

- An effective operational system has been established for the intensive maintenance of sand-based turf in golf course greens, regulating (limiting) carbon exchange. Elements of the system include nitrogen fertilization, maintained moisture, stress occurrences, and the condition of the turf both above and below the surface.

• The pathway of carbon in sand-based turf is tracked, including its acquisition from mowed green biomass and root system development, as well as carbon emissions resulting from the decomposition of dead plant material on the surface and the mineralization of some roots in the moist subsurface environment.

• The operational system for intensive turf maintenance is based on remote monitoring of various indicators to establish pre-threshold levels, and it predicts the future state of the turf through Bayesian network decisions and Artificial Intelligence, enabling specific operations to optimize nitrogen fertilization, irrigation rates in the sand substrate, and turf height.

• The spatial variability of moisture and nitrogen availability in the sand substrate is determined using actual stress data reflecting seasonal manifestations of microrelief and surface conditions. This provides a scientifically justified distribution and diagnosis of the monitored indicators to achieve optimal irrigation without overuse of fertilizers and water.

• Root system development in the turf serves as an indicator of the applied intensive maintenance system across seasons. Significant differences are observed under contrasting management regimes and meteorological conditions, with fertilization and particularly irrigation substantially affecting root mass.

• A high-precision U-Net module standardizes turf-only distribution over specific areas (AOIs) and removes side effects outside the vegetation index (VI) zones, allowing for consistent multi-year monitoring of heterogeneous golf course images. Multi-season clustering condenses extensive VI archives into repeatable turf surface regimes, while similarity analysis identifies stable, effective vegetation indices (VI) in groups (structural NIR-based, color-stress soil-corrected, red-edge, and nonlinear/saturated). This represents a principled strategy for maintaining turf in the desired condition using surface objects.

• The study proposes an applicable model in which previously collected data based on a Bayesian Network (BN) from prior condition tables (CPTs) are updated with current site-specific data, and a corresponding maintenance regime is developed. The Bayesian Network is activated on independent golf course data using observed indicators that account for imbalances, while calibration and diagnostic approaches quantify probabilistic reliability. The system allows for extreme scenarios and renders decisions unambiguous under uncertainty, ensuring the combination of nitrogen supply with the required moisture for the turf in its entirety-both above and below the surface.

Scientific Applied Contributions:

A practical decision-making system has been developed for the intensive management of sand-based golf turf, integrating data from sensors, remote sensing methods, and field observations. This system provides scientifically grounded recommendations for nitrogen fertilization, irrigation, and mowing with the goal of optimizing the carbon balance.

Specific management options for fertilization and irrigation are proposed, which reduce water and mineral fertilizer use without compromising turf quality, while simultaneously limiting nitrogen losses and improving resource use efficiency.

Remote indicators (vegetation indices and proxy indicators) have been introduced as practical tools for early diagnosis of stress, nutrient deficiencies, and changes in the physiological condition of the turf, enabling timely and precise corrective actions.

Practically applicable threshold values for moisture management in the golf profile (VWC) have been developed, which can serve as reference points for applying irrigation in case of deficits, aiming to enhance long-term sustainable carbon sequestration.

A methodology has been created for integrating scientific knowledge and field data into an applicable model that can be adapted to different sites, climatic conditions, and types of turf systems.

The dissertation provides a scientifically grounded framework for sustainable golf course management, which can be used by practitioners, consultants, and designers to reduce carbon emissions, minimize environmental impact, and improve public perception of the golf industry.

7. Critical Notes and Questions

Notes:

- The study focuses on sand-based golf greens with *Agrostis stolonifera L.* as the main living element. The dissertation lacks a description of this species, its biological characteristics, longevity under maintenance, seasonal growth patterns, and influencing factors.
- The term "soil" is used incorrectly; the artificial surface layer (mainly sand and turf) is not soil.
- The mixing of Bulgarian and unnecessary foreign terms with Latinized words in the abstract makes the text hard to understand. Clearer Bulgarian explanations with Latin terms in parentheses are recommended.

Questions:

- Was additional overseeding applied to the turfgrass beyond initial sowing 16–20 years ago?
- What explains the observed seasonal differences in root depth in 2023–2024? Are longer or shorter roots solely due to days without water stress? Does this suggest that root systems adjust deeper or shallower layers depending on stress conditions in the previous season?

8. Published Articles and Citations.

The candidate has published three scientific articles related to the dissertation. One is co-authored with the supervisor, published in the International Conference on Energy Efficiency and Agricultural Engineering (EE&AE) – indexed in Scopus. Two articles are sole-authored. Publication activity meets the minimum scientometric requirements for the PhD degree.

The presented author's abstract objectively reflects the dissertation's structure and content, is sufficient in length, and well-illustrated.

CONCLUSIONS:

Based on the various research methods applied and mastered by the PhD student, the correctly designed experiments, and the conclusions and generalizations drawn, I consider that the presented doctoral dissertation meets the requirements of the Law on the Development of the Academic Staff in the Republic of Bulgaria (ZRASRB) and the Regulations of the Agricultural University for its implementation, which gives me grounds to evaluate it **POSITIVEL7Y**.

I would like to respectfully propose that the esteemed Scientific Jury also vote positively and award Ivelin Dimitrov Markov – a full-time PhD student at the Department of •Crop Science, Agricultural University, Plovdiv – the educational and scientific degree of "**Doctor**" in the scientific specialty "Forage Production, Grassland Management."

05.03.2026
Plovdiv