OPINION

on a dissertation for obtaining the educational and scientific degree "**Doctor**" in: field of higher education 6. "Agrarian Sciences and Veterinary Medicine", professional direction 6.1. "Plant Production", scientific specialty "Forage Production and Grassland"

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Topic of the 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: Prof. Dr. Aneliya Ilieva Katova, Institute of Forage Crops - Pleven at the Agricultural Academy; field of higher education "Agrarian Sciences and Veterinary Medicine", professional direction 6.1. "Plant Production", scientific specialty "Plant breeding and Seed Production of Cultivated Plants", appointed as a member of the scientific jury by order No. RD-16-209/02.02.2026 by the Rector of the Agricultural University - Plovdiv.

1. Relevance of the problem.

Created more than 5 centuries ago on the vast green lands of Scotland, golf ranks among the most popular sports. With more than 70 million fans worldwide, 26 million in the United States and more than 15 million in Europe, golf has become a hugely profitable industry. Two decades ago, golf found its best place on the Bulgarian Black Sea Coast and in 2008, "BlackSeaRama Golf" was opened, the first championship golf course in Bulgaria, designed by the famous golfer Gary Player, and there are already over 10 professional courses in our country. The construction of golf courses requires significant resources, and their sustainable management and the implementation of environmental practices are essential to minimize environmental impact. Green spaces can help in the fight against carbon dioxide reduction, alleviate the heat effect by reducing energy consumption and global warming. Golf courses are part of green infrastructure and are ecosystems that include grass cover (turf), soil, water and surrounding flora and fauna. Putting greens are specially maintained areas of very short grass, requiring extreme precision, a smooth surface and regular maintenance. Growing concerns about climate change, water scarcity and nutrient runoff necessitate the implementation of precision turf management. The integration of real-time soil and weather sensors, vegetative indices from unmanned aerial vehicles (UAVs) or satellite imagery, and AI-based analytical approaches creates the opportunity to increase irrigation and fertilization efficiency, reduce nutrient losses, and detect stress in turf grass earlier and more precisely than visual observation alone. All of this together is the subject of the dissertation work and emphasizes its relevance by applying state-of-the-art predictive models and decision-making systems, with an innovative focus.

2. Purpose, tasks, hypotheses and research methods.

The aim is to investigate how different sustainable turf grass management practices affect soil carbon sequestration on intensively maintained sand-based greens and how these practices affect the annual carbon budget. The dissertation is organized into five interrelated parts: 1: Nitrogen fertilization optimization; 2: Irrigation optimization; 3: Root system development; 4: Vegetation indices and remote sensing; and 5: Artificial Intelligence (AI)-based Bayesian Decision Support System (BN-DSS). The methodological workflow is summarized schematically in Figure 3, which links the primary objective to four

secondary objectives. The study employs an observational design rather than a controlled, replicated field experiment. Each location represents a different agro ecological and management context that reflects the real-world constraints on decision-making in the maintenance of two different geographically distant golf courses in Bulgaria and China. Meteorological and evapotranspiration (ET) data are from automated weather stations at each site, recorded at 15-min intervals, and generate hourly and daily summaries. These data support: growth potential (GP) calculated from air temperature for the metabolic activity of cool season grass species, in this case, bent grass (*Agrostis stolonifera* L.), and modeling of N demand; ET_0, and Kc values. Multiple methods for research, prediction, and analysis are described in detail and applied in the study on the sustainable management of intensively maintained sand-based putting greens and provide input for an integrated SMART decision support system (DSS).

3. Visualization and presentation of the obtained results.

The dissertation contains 10 parts: Introduction - 8 pages, Literature review - 55 pages, Aims and objectives - 3 pages, Material and methods - 42 pages, Results and Discussion - 89 pages, Conclusions - 2 pages, Contributions - 4 pages, Future directions - 5 pages, Literature - 25 pages. The research was conducted during the period 2019 - 2025 on two golf courses in Bulgaria and China. The dissertation is in English, has a volume of 243 pages and contains 43 tables and 94 figures.

4. Discussion of the results and used literature.

The cited literature includes 456 sources in Latin, 66% of which are after 2010, including 35% - from the last 5 years, the most modern. The doctoral student shows a high level of theoretical knowledge, skillfully interprets his own results, in comparison with the world scientific literature. The scientific and practical goal of defining maintenance regimes that preserve elite turf quality while simultaneously improving the net soil carbon balance and reducing unnecessary resource use is achieved based on the concept of sustainable development as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Essentially, this means making the best use of limited resources (water, land, natural resources) to minimize their depletion, as well as taking into account the long-term consequences of their use (what their long-term impact might be). The work is positioned both as a scientific framework and as an operational path towards a more resource-efficient, carbon-conscious management of sand-based putting greens. The dissertation integrates four management technology units: nitrogen fertilization, irrigation strategy, root system development and turf surface condition, in a general understanding of soil carbon deposition in intensively managed sand-based putting greens. Within the framework of the experiments, modeling and analysis through remote sensing, the results lead to 8 logical conclusions, which I fully accept.

5. Contributions of the dissertation work.

Six scientific, 6 scientific-applied and 1 practical contribution have been formulated:

Scientific contributions

1. A carbon-aware framework for a “narrow operating range” for sand-based putting greens is created. Four controllable technology units (N, irrigation, roots, turf surface condition) are linked to two carbon pathways: carbon sequestration, driven by cut volume production and root turnover, and carbon losses, driven by moisture-induced mineralization, thatch breakdown, and stress constraints.

2.Temporal dynamics of irrigation were established with applicable thresholds for volume water capacity (VWC) and ETc. The irrigation analysis determined the moisture behavior of the sand profiles as a narrow operating range, with an upper plateau driven by drainage and increased instability upon depletion.

3.Spatial heterogeneity of irrigation has been established as a diagnostic layer within the green, which determines the real exposure to stress, the area shares by moisture classes and the clustering of time series reveal persistent dry and wet areas and their seasonal stability.

4.A root system module has been created to establish seasonal rooting trajectories and sustainable treatment hierarchies under contrasting irrigation regimes. Deficit-oriented irrigation supports deeper and more persistent roots during heat waves.

5. A defensible remote sensing workflow with turf-only AOIs and interpretable VI compression is created using a highly accurate U-Net semantic segmentation module that standardizes turf-only AOIs and eliminates out-of-area contamination from VI time series, enabling consistent multi-year monitoring on heterogeneous golf course imagery. Multi-season clustering compresses large VI archives to repeatable turf surface modes, and similarity analysis defines robust functional VI families (structural NIR-based, color-stress, soil-corrected, red-edge, and nonlinear/saturated).

6. Probabilistic Integration and Validation of Bayesian Network DSS. A reproducible knowledge-to-model path is established. The Bayesian network is validated on independent putting green data using accuracy and class imbalance metrics and calibration diagnostic approaches. The framework allows for counterfactual scenarios by providing an integrating layer that links water regime, nitrogen fertilization, turf surface condition, and root constraints into a single decision object.

Scientific and applied contributions

1. A carbon-aware operational logic for decision-making in sandy greens is introduced, through a diagnostic list of management indicators on a daily to weekly scale: avoiding chronic moisture and nitrogen oversupply, which accelerate decomposition and losses; avoiding chronic deficiency, which leads to a collapse of root growth and turnover; proactive management of short stress waves; and protecting rooting depth as a guarantee of resilience and carbon allocation

2. Irrigation planning rules based on VWC and ETc thresholds applicable to sandy greens were created: maintaining VWC in a stable range of 18–26%, treating ~16–18% as the depletion limit ("start of irrigation"), and treating ~28–30% as the drainage ceiling/ adverse irrigation to avoid excess application and potential leaching below sensor depth.

3. Spatial remediation workflow for uneven moisture. This intra-green layer provides a practical way to reduce localized stress and saturation risk and increase confidence in irrigation decisions.

4. Predict root mass loss risk to refine irrigation thresholds and "nitrogen" safety margins by proactively adapting water and nitrogen solutions based on belowground capacity, not just aboveground symptoms.

5. VI evidence nodes for routine monitoring and integration into DSS. A compact, interpretable set of representatives of VI families for evidence in DSS is proposed: structural index (NDVI or GNDVI), color-stress index (MGVRI or VARI), soil-corrected index (MSAVI) and, if necessary, red-edge index (NDRE), when biochemical gradients are informative.

6. BN-oriented support for decisions with uncertainty and counterfactual evaluation. BN-DSS translates empirical results into operational probabilistic reasoning: it updates the state of the object through sensory and VI evidence and supports counterfactual evaluation of different scenarios.

Practical Contribution: A functional, modular dashboard has been developed as a user layer for implementing SMART BN-DSS, which translates thresholds and state definitions into operational decisions on a daily to weekly scale. The dashboard consolidates meteorological and sensor evidence, calculates shared derived drivers from all modules (GP, ET/ETc, stress indicators), and presents consistent interpretations of

states for irrigation, fertilization, root development, turf surface monitoring, and organic matter dynamics. The dashboard enables site-specific historical diagnostics, short-term planning and scenario exploration, while maintaining a verifiable trail of actions and results. By integrating temporal rules (threshold-based planning), spatial diagnostics (zonal moisture interpretation) and remote evidence (AOI-based VI trajectories and heat maps), it provides a coherent interface for adaptive management and supports carbon-conscious optimization within routine maintenance constraints.

6. Critical notes and questions.

➢ The dissertation and the abstract lack a list of abbreviations used in Bulgarian and English.

➢ The abstract in Bulgarian contains many foreign words and 50% Bulgarian, with the titles of the tables and figures being entirely in English. The noun fertilizer is masculine!

➢ Table 3 in the abstract, thus presented with 18 abbreviations, in 18 cells in English is incomprehensible, it concerns vegetation indices from satellite images.

1. Is there information on what varieties of creeping bent grass (*Agrostis stolonifera* L.) are sown and maintained on the two golf courses in Bulgaria and China?

2. Considering the longevity of the perennial grass species and the years of creation and use of the two golf courses studied (16 and 20 years), was undersowing applied and with what?

7. Published articles and citations.

In connection with the dissertation work, the following have been published: 1 article co-authored with the scientific supervisor in a scientific publication, referenced and indexed in a global database of scientific information (Scopus) and 2 independent articles in a scientific journal and proceedings. The publications are related to the topic of the dissertation work and collect 35 points and cover the minimum points for acquiring the ESD "Doctor" according to the ZRASRB. Probably because the articles were published less than a year ago, their citations have not yet been noticed.

The presented abstract objectively reflects the structure and content of the dissertation work.

CONCLUSION:

Based on the numerous modern, innovative research methods and approaches learned and applied by the doctoral student, the correctly conducted experiments, the generalizations and conclusions made, I believe that the presented dissertation meets the requirements of the Law on the Development of Academic Staff in the Republic of Bulgaria and the Regulations of the Agrarian University for its application, with a contribution to the digitalization and introduction of AI, in the precise management of green ecosystems (golf courses, putting greens, with intensive maintenance, with the aim of a positive C balance), which gives me reason to evaluate it **POSITIVELY.**

I am impressed by the professional training and expertise of over 18 years of experience in the golf industry - course construction and their precise maintenance, in parallel with training and diplomas from Universities in Scotland, Finland, China, Canada and Bulgaria - on three continents.

I would like to propose to the esteemed Scientific Jury to also vote positively and award Ivelin Dimitrov Markov the educational and scientific degree "doctor" in the scientific specialty "Forage production and grassland", professional direction 6.1. "Plant growing".

Date: 05.03.2026 **PREPARED (**
city of Pleven