



OPINION

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: Prof. Dr. Viliana Marinova Vasileva, Maize Research Institute – Knezha, Agricultural Academy, Field of Higher Education 6.1. Agricultural Sciences and Veterinary Medicine, Professional Field: Crop Science, Scientific Specialty “Crop Science”, 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. Relevance of the problem.

The topic of the dissertation is highly relevant. Considering the intensity of turf systems, particularly sand-based putting greens, the practices for their sustainable management and the potential for carbon accumulation in the soil are of particular importance. The requirements for golf courses (in our country about 10 with 18 holes, golfbreaks.com), given their specific nature, are high. Maintaining them requires frequent mowing at very low heights, precise fertilization, and planned irrigation. These operations can be resource-intensive, increasing consumption of water, energy and nutrients, while simultaneously raising the risk of unintended consequences when practices are not aligned with both plant needs and soil capacity. At the same time, the environment must be protected. As intensive systems, they increase the carbon footprint. A primary management challenge is achieving a neutral or positive carbon balance without compromising the playing surface.

Current realities, viz. resource availability, climate change and other factors require the adoption of precision techniques that facilitate correct decision-making. Although these techniques are widely used in agriculture, their implementation in turf systems is still limited. Integrating real-time soil and meteorological sensors, vegetation indices (VIs) from UAV or satellite imagery, and AI-based analytical approaches offers an opportunity to increase the efficiency of turf management operations compared with ordinary visual observations.

At present, putting greens are constructed to USGA specifications (United States Golf Association), using sand-based rootzone profiles (sand content not less than 90%) with amendments to improve water and nutrient retention. The low organic matter content facilitates carbon loss. Greens are mown daily, and twice daily during tournament events, at very low heights (1.8 to 3 mm). Low mowing reduces leaf area, limits photosynthesis, and can restrict root system development.

Nitrogen fertilization is a key factor for turf quality and functionality, but it can be inefficient when not matched to the physiological needs of the species grown. Excessive accumulation of organic matter can compromise playing characteristics and rootzone function, even as it may increase carbon storage. Irrigation management is equally critical. Maintaining appropriate soil volumetric water content (VWC) requires avoiding water stress (deficit/overwatering).

Finding the balance between management and desired outcomes is a difficult process. Therefore, a scientific and practical aim is to define maintenance regimes that preserve elite turf quality while simultaneously improving the net soil carbon balance and reducing unnecessary resource use.

The above justifies undertaking the large-scale study presented in the dissertation. Management practices - one aspect examined in the dissertation are important for soil carbon accumulation/loss and the environmental management of sports turf.

2. Aim, objectives, hypotheses, and research methods.

The doctoral candidate formulates one main and five secondary objectives. The primary objective was how different sustainable turf management practices impact soil carbon sequestration on intensively maintained sand-based putting greens and how these practices affect the annual carbon budget.

The secondary objectives are: i) Optimizing nitrogen fertilization in turfgrass management. To quantitatively determine the environmental drivers of nitrogen demand in putting greens planted with *Agrostis Stolonifera*, and to develop predictive models integrating GP, vegetation indices (VIs) and stress-adjusted environmental indicators to optimize nitrogen application within a SMART DSS; ii) Optimizing irrigation, water-use efficiency and moisture-related stress in sand-based putting greens. To determine how different irrigation strategies (fixed schedule versus adjustments based on ET_c and soil moisture) affect soil water dynamics, water-use efficiency (WUE) and moisture stress in intensively maintained sand putting greens, and how these relationships can support an AI-based decision-support system; iii) Monitoring root-system development under deficit irrigation. To assess how deficit versus daily irrigation and associated environmental factors influence root length of *Agrostis Stolonifera* and how these relationships can be incorporated into predictive monitoring models within the DSS; iv) Remote sensing and vegetation indices as turf-management tools. To evaluate how satellite, UAV and ground-based vegetation indices reflect turf responses to environmental drivers and management practices, to determine their sensitivity to stress and resource use, and to establish how these signals support predictive modelling and integration into an AI-based DSS; v) AI-based Bayesian decision-support system (BN-DSS). To build, calibrate and evaluate a DSS based on a Bayesian network that integrates experimental results from the literature, local monitoring data and machine-learning outputs into a single, interpretable framework for sustainable resource management of intensively maintained sand putting greens.

The methodology is effectively illustrated in a synthesized figure. The dissertation is organized into five interrelated parts that together address sustainable management of intensively maintained sand-based putting greens and provide input data for an integrated SMART decision-support system (DSS). The parts are: Part 1. Optimization of nitrogen fertilization; Part 2. Optimization of irrigation; Part 3. Root-system development; Part 4. Vegetation indices and remote sensing. All parts 1–4 contain detailed activities serving as input sources for Part 5. AI-based Bayesian decision-support system (BN-DSS).

The study applies an observational (unreplicated) design rather than a controlled, replicated field experiment. The research was conducted at two heterogeneous locations — Golf Course A (GCA) and Golf Course B (GCB). Golf Course A (GCA) is located at 43.41°N, 28.22°E, about 1 km from the Black Sea, at 175 m above sea level, with a moderate-continental climate influenced by maritime proximity (mean annual T ~12°C; summer maxima ~32°C; winter minima ~-2°C; annual

precipitation ~550 mm, concentrated in spring/autumn, with frequent summer droughts). The 2023–2024 growing seasons (Mar 1–Oct 30) were dry (335 mm and 480 mm precipitation), with warmer conditions in July–August and increased seasonal ET (910 mm and 955 mm). The greens are constructed to USGA specifications (approximately 95% sand and 5% zeolite). After roughly 12 years of suboptimal maintenance, organic matter content in the upper 5 cm is 6–8%. The turf surfaces are 16 years old. Mowing height during the growing season is 3.0–3.2 mm; rolling is rare, only for events.

Golf Course B (GCB) is located at 39.16°N, 116.99°E, about 10 m above sea level and roughly 70 km inland from the Bohai Sea, with a humid continental climate strongly influenced by monsoon (hot humid summers up to 35°C; annual precipitation ~590 mm; combined July–August precipitation ~600 mm in 2023 and 2024; cold dry winters down to -12°C). Its greens are also built to USGA-based standards, with a rootzone composition of 94% sand, 4% silt, 2% clay; pH 6.3–6.8; OM maintained at ~2.0%; mowing at 3 mm and daily rolling. The turf species used at both sites was *Agrostis Stolonifera*.

Meteorological and ET data were collected at both sites. Soil and root measurements were performed. Soil samples for agrochemical analysis were taken from three depths (0–25 mm, 25–50 mm and 50–75 mm). Manual TDR sensors were used to measure VWC weekly. Turf and root measurements were carried out.

Activities related to the five parts are described in detail, including the four steps of Part 5: development of an AI-based SMART/DS framework integrating knowledge extracted from the literature with site-specific data.

3. Visualization and presentation of the results obtained.

The dissertation is structured as follows: Introduction, Literature Review, Aims and Objectives, Materials and Methods, Results, Discussion, Conclusions, Contributions, Future Directions, References. The Introduction consists of 4 subsections; the Literature Review comprises 7 subsections. The Aims and Objectives, as noted above, are well formulated. Materials and Methods include 5 parts, and the Results and Discussion sections follow chronologically the five parts described in the previous section.

The dissertation is 243 pages long. The Results and Discussion sections occupy the largest share of the structure - more than one-third of the total length. The results are illustrated in tables (43 total) and 94 figures of various designs.

4. Discussion of the results and references used.

The dissertation integrates four management levers, i.e. nitrogen input, irrigation strategy, root system development, and turf surface condition into a comprehensive understanding of soil carbon sequestration in intensively managed sand-based putting greens. Each of these levers is accompanied by an in-depth discussion.

The experimental results obtained are discussed logically and demonstrate a strong capacity for analysis, which has been greatly supported by the doctoral candidate's education and the numerous professional development courses undertaken. A thorough discussion, analysis, and corresponding conclusions have been presented in a style that significantly exceeds the level typically expected of a doctoral candidate. All sections are written in a high scientific style.

The cited literature includes 456 sources in Latin script, of which 195 (45.8%) have been published within the last ten years. The referencing of more than 400 literature sources is clear evidence of the author's excellent familiarity with the scientific field. It should also be emphasized that the results obtained in the study are skillfully compared with those reported in the literature.

5. Contributions of the doctoral dissertation.

A total of six scientific contributions, six scientific-applied contributions, and one practically applicable contribution were formulated.

Scientific Contributions

1. Carbon-aware operating-envelope framework for sand-based putting greens. The framework links four controllable management levers (nitrogen fertilization, irrigation, root system condition, and turf surface status) with two carbon pathways: carbon inputs, determined by clippings production and root turnover, and carbon losses, determined by moisture-driven mineralization, thatch decomposition, and related processes.
2. Explainable temporal irrigation dynamics with actionable VWC and ETc thresholds.
3. Spatial irrigation heterogeneity as a within-green diagnostic layer.
4. Root system development as a mechanistic mediator between management and belowground allocation.
5. Defensible remote-sensing pipeline for turf-only AOIs and interpretable VI compression.
6. Probabilistic integration and validation of a Bayesian Network DSS.

Scientific-Applied Contributions

1. Carbon-aware operational decision logic for sand-based greens.
The operating-envelope framework is transformed into a practical decision-making logic and a diagnostic checklist for management on a daily to weekly scale: avoiding chronic moisture and chronic nitrogen oversupply, which accelerate decomposition and losses; avoiding chronic deficits that lead to a collapse of growth and root turnover; proactively managing short stress waves; and protecting rooting depth as a guarantee of resilience and carbon distribution.

This applied framework supports field diagnostics in determining whether carbon risk is dominated by moisture, oversupply, deficit, or recurrent stress, rather than assuming that turf performance alone is a sufficient proxy indicator of sustainability.

2. Irrigation scheduling rule-set from VWC and ETc state thresholds.
3. Spatial remediation workflow for patchy moisture.
4. Root-risk forecasting to refine irrigation thresholds and nitrogen safety margins.
5. Implementable VI evidence nodes for routine monitoring and DSS integration.
6. BN-enabled decision support with uncertainty and counterfactual evaluation.

Practically applicable scientific contribution – operational implementation of a SMART dashboard.

A functional, modular dashboard has been developed as a practical decision-support tool. The dashboard enables site-specific historical diagnostics, short-term planning, and scenario exploration, while simultaneously maintaining verifiable records of management actions and their outcomes.

The doctoral candidate's realistic and critical perspective on the research problem is reflected in the sections Limitations and Future Directions.

In conclusion, the dissertation represents a valuable contribution to the management of turf systems in the context of sustainability and a positive carbon balance.

6. Critical remarks and questions. None.

7. Published articles and citations.

The doctoral candidate published three scientific papers: one co-authored with the supervisor in a scientific journal in internationally recognized journal, indexed in internationally recognized databases for scientific information (Scopus), and two papers authored independently.

The submitted author's abstract of the dissertation objectively reflects the structure and content of the dissertation.

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 **POSITIVELY**.

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.”

Date: March, 01, 2026.

THE OPINION

Подписите в този документ са заличени

във връзка с чл.4, т.1 от Регламент (ЕС) 2016/679

(Общ Регламент относно защитата на данни).