



REVIEW

of a dissertation submitted for the award of the educational and scientific degree “Doctor” in: Field of Higher Education 6.0 Agricultural Sciences and Veterinary Medicine, Professional Field 6.1 Crop Production, Scientific Specialty “Forage Production and Grassland Management”.

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

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

Reviewer: Prof. Dr. Hristina Georgieva Yancheva, Agricultural University – Plovdiv, Field of Higher Education 6.0 Agricultural Sciences and Veterinary Medicine, Professional Field 6.1 Crop Production, Scientific Specialty “Forage Production and Grassland Management”, appointed as a member of the scientific jury by Order No. RD 16-209/02.02.2026 of the Rector of AU.

1. Brief presentation of the candidate

Ivelin Dimitrov Markov was born on March 25, 1982, in Varna. In 2005, he obtained a Bachelor’s degree in “Automation, Information and Control Computer Systems” from the Technical University of Varna. In 2016, he graduated with a Master of Engineering from the same university.

Between 2006 and 2023, he completed training at several foreign universities, primarily in courses related to golf course design and management. From 2018 to 2023, he worked as a team manager at BlackSeaRama Golf Course in Balchik. Since the beginning of 2023, he has been enrolled as a full-time PhD student at the Agricultural University – Plovdiv, Department of Crop Production. For two years (2023–2025), the PhD student pursued training and conducted part of his scientific research at Tianjin Agricultural University, China.

2. Relevance of the research problem

The sustainable management of turf systems under intensive maintenance, such as golf course putting greens, is gaining increasing importance in the context of global environmental challenges and climate change. These turf systems, particularly when constructed on sand-based substrates, represent a specific ecosystem component characterized by highly dynamic water, nutrient, and gas interactions. Under conditions of intensive management - including frequent mowing, irrigation, fertilization, and aeration - the processes of soil carbon sequestration and the annual carbon budget may be significantly altered, affecting ecosystem sustainability and its role in the global carbon cycle.

In recent years, the scientific community, landscape management specialists, and practitioners have shown growing interest in developing and implementing practices that optimize the ecological benefits of turf areas, reduce greenhouse gas emissions,

and improve soil organic carbon stocks. Golf courses, and especially putting greens with their high intensity of use, provide an ideal system for studying these processes, as they combine intensive agronomic measures with high requirements for turf quality, resilience, and functionality.

Understanding the influence of various sustainable management practices - including minimizing the use of chemical fertilizers, applying organic amendments, optimizing irrigation regimes, and improving soil structure - and their impact on carbon sequestration and the annual carbon budget is essential for achieving a balance between high playing surface quality and environmental responsibility. The topic of the dissertation is highly relevant from both scientific and applied perspectives, as the results may support practical management guidelines, sustainable use policies, and the assessment of ecosystem services of turf areas under conditions of climatic and socio-economic change.

3. Aim, objectives, hypotheses, and research methods

The main objective of the research is to develop and validate an integrated, reproducible framework for turfgrass management support that utilizes Bayesian networks, remote sensing, and field data for adaptive, resource-efficient, and carbon-aware decision-making.

The study is based on the following working hypotheses:

- Root status functions as a key mechanistic mediator between management regimes and belowground ecological processes.
- Integration of remote, sensor, and meteorological data through probabilistic modeling improves the accuracy and interpretability of management decisions.
- Compression and clustering of vegetation indices lead to robust and functionally meaningful representations of turf surface condition.
- A modular dashboard can effectively translate complex model relationships into practical real-time decisions.

The dissertation is structured into five interrelated parts that collectively address the sustainable management of intensively maintained sand-based putting greens and provide input data for the development of an integrated SMART Decision Support System (DSS).

Part 1 examines the optimization of nitrogen fertilization through modeling nitrogen requirements based on growth potential (GP), vegetation indices, and environmental factors.

Part 2 focuses on irrigation optimization by comparing fixed and evapotranspiration (ET)-based strategies and defining key thresholds for planning and DSS integration. Part 3 analyzes root system development and its relationships with management practices and environmental conditions.

Part 4 evaluates the applicability of vegetation indices and remote methods, including computer vision, for providing spatially detailed management indicators.

Part 5 integrates the results into an AI-based Bayesian DSS that offers site-specific recommendations balancing turf quality, resource efficiency, and soil carbon sequestration.

The research was conducted during the period 2019–2025 at two golf courses located at different latitudes in Bulgaria and China.

The methodological framework includes a combination of:

- Analysis of field and sensor data related to water balance, plant stress, and root dynamics;
- Remote sensing studies and time-series processing of vegetation indices;
- Machine learning for segmentation, clustering, and data reduction;
- Probabilistic modeling through Bayesian networks to describe cause-and-effect relationships;
- Development and testing of an interactive decision-support dashboard.

The selected combination of objectives, tasks, hypotheses, and research methods contributes both theoretically and practically to the development of intelligent systems for adaptive management of turf ecosystems.

4. Presentation and visualization of the obtained results

The dissertation submitted for review is written in English, comprises 243 pages, and is structured into 10 main sections: Introduction, Literature Review, Aims and Objectives, Materials and Methods, Results, Discussion, Conclusions, Contributions, and References.

The dissertation includes a total of 43 tables and 94 figures, which clearly and systematically illustrate the obtained results and derived conclusions.

In addition to the main structure, a separate section entitled “Risks and Directions for Future Work” has been included, adding further completeness to the research and outlining a clear perspective for its further development. This section defines two complementary directions for future scientific work: deepening the causal and probabilistic architecture of the BN-DSS and expanding its empirical and operational scope through application across different sites, diverse data streams, and varied decision-making contexts.

5. Discussion of the Results and Literature Used

The presentation and discussion of the results are distinguished by a very high scientific standard, accurate and consistent use of specialized terminology, and argumentation supported by relevant evidence from the international scientific literature. The doctoral candidate has developed an exceptionally comprehensive and in-depth literature review based on 456 international scientific sources, fully covering contemporary research, concepts, and methodological approaches directly related to the topic under investigation. This solid theoretical foundation enables the experimental and modeling results obtained to be critically analyzed within a broad context and clearly linked to established scientific knowledge.

Concerning the optimization of nitrogen fertilization and the dynamics of the System Object Model (SOM), the results show that turfgrass response to nitrogen application is rapid and depends on the type of indicator used. Under single-rate fertilization, the strongest relationship is observed for the Digital Visual Index (DVI) with a 2-day lag ($r = 0.270$), whereas under cumulative nitrogen rates, GOSA VI is dominant with a 5-day lag ($r = 0.252$). These temporal windows reflect the period required for turf density and chlorophyll signal to respond after fertilization. The combination of several vegetation indices into composite signals leads to more stable and stronger relationships.

Models based solely on vegetation indices (VI) (training 2023, testing 2024) successfully reproduce seasonal dynamics but smooth out abrupt changes. Turf condition described by vegetation indices explains approximately 37-40% of the

variation in applied nitrogen rate and cumulative N removal but does not capture sudden peaks and declines during the season. This indicates the need to include additional predictors related to environmental stress.

The analysis of meteorological stress factors shows that the effects of drought and heat waves are clearly reflected in vegetation indices. Different indices respond to different types and durations of stress: structurally sensitive indices reflect short-term drought events, while chlorophyll-sensitive indices capture more prolonged heat stress. This is physiologically consistent and confirms that spectral signals carry reliable information about environmental pressure on the turf surface.

The inclusion of lag-aligned indicators of heat and moisture stress alongside vegetation indices leads to a substantial improvement in nitrogen fertilization models. For applied nitrogen rates, the combined model (VI + stress) significantly increases the explained variance ($R^2 \approx 0.55$ compared to ≈ 0.37 with VI alone), indicating that fertilization management decisions are strongly dependent on short-term stress conditions. The most significant drivers are short-term water deficits and accumulated heat, while spectral indices play a more stabilizing role. For cumulative nitrogen rates, the addition of stress indicators results in a more moderate improvement: the global composite of vegetation indices remains dominant, while medium-term drought signals modulate cumulative nitrogen uptake.

SHAP analyses (based on machine learning and explainable artificial intelligence for providing site-specific recommendations) confirm a clearly expressed causal hierarchy: short-term stress controls rapid nitrogen application decisions, whereas turf condition determines cumulative effects. The analysis of the System Object Model (SOM) for the period 2019–2024 shows a long-term decrease in organic matter in surface soil layers, clear spatial differentiation, and a strong positive relationship between annual nitrogen input and SOM content at all depths. In summary, the nitrogen module of the DSS can be described as a system with a fast cycle, driven by stress and realized growth, and a slow cycle in which the System Object Model integrates the multi-year consequences of management decisions and functions as a sustainability indicator.

Irrigation optimization is based on integrating temporal rules (Golf Course A – GCA) and spatial diagnostics (Golf Course B – GCB) into a unified DSS logic. GCA describes soil moisture dynamics over time through current moisture content, the adjusted evapotranspiration coefficient, and an optimal moisture window. GCB adds spatial modifiers that explain local zones of stress or oversaturation despite acceptable average values. Within the DSS, temporal variables determine baseline irrigation decisions, while spatial indicators adjust risk and guide zone-specific management actions.

The in-depth analysis of results from Golf Course A (2019–2024) shows a stable and well-managed soil moisture regime, in which the green spends most of the season under moderate stress without entering severe stress conditions. The spatial analysis of Golf Course B (2024) reveals that despite good average moisture levels within the greens, persistent dry and wet zones exist. Uniformity improves over the season, but some greens exhibit periods of increased heterogeneity associated with stable spatial clusters. This demonstrates that effective irrigation requires not only temporal moisture control but also spatially targeted management actions.

The results concerning root system development show a pronounced seasonal dynamics with a spring peak and summer decline, with irrigation regime as the main controlling factor, especially during heat waves. This effect is stable across years and spatially consistent within the green. Fertilization intensity modifies the distributions but

does not alter the fundamental hierarchy between regimes. Two complementary root signals for the DSS have been identified: (i) a seasonal, stress-sensitive trajectory in which water density consistently stabilizes root length during heat waves; and (ii) an operational proxy layer, in which a limited number of lagged vegetation indices - preferably in a low-dimensional composite - can track and moderately improve root length predictions when combined with environmental drivers. Together, these results define discretized BN states for “root status” and allow root depth to function as a medium-term constraint both in selecting irrigation thresholds and in defining nitrogen safety margins under sandy conditions.

Based on separate, evidence-rich analytical components - nitrogen dynamics and SOM dynamics, irrigation thresholds and spatial heterogeneity, root responses and vegetation proxy indices, as well as an operational remote sensing workflow - an AI-based intelligent DSS framework has been developed to support management decisions. This framework follows four main steps and integrates knowledge from the literature with site-specific data. The presentation of the results deliberately preserves the methodological context to clarify how the Bayesian Network (BN) functions, how it is constructed, and how it is validated with real data from putting greens.

In conclusion, the analytical components of the dissertation are integrated into a unified probabilistic system that predicts key turfgrass states with good accuracy and interpretable uncertainty. The system remains open to calibration as new data become available and enables clear counterfactual comparisons between alternative management strategies.

6. Contributions of the Dissertation

Based on the conducted experiments, remote sensing observations, modeling, analyses, and the obtained results, original scientific and applied scientific contributions have been formulated and are presented here in summarized form. The doctoral candidate proposes a scientifically grounded solution for the management of sand-based putting greens on golf courses. The contributions are based on studies conducted for the first time in Bulgaria and expand the existing knowledge in the fields of turfgrass management, soil hydrology, and sustainable water resource use.

Methodologies have been developed for assessing the water regime and nutrient balance in sand-based constructions, adapted to the specific climatic conditions of the country. Practical recommendations have been derived for optimizing irrigation, fertilization, and aeration practices to achieve high turf quality while simultaneously reducing water and fertilizer inputs. The proposed models and algorithms enable forecasting of green conditions under different climate stress scenarios and varying intensities of use.

The obtained results have both theoretical value for advancing scientific research in the field and direct practical application in the design, maintenance, and sustainable management of golf courses and other high-quality sports turf areas.

Scientific Contributions

1. A carbon-aware conceptual framework for a “narrow operational range” in intensively maintained sand-based putting greens has been developed, formalizing the interactions among nitrogen management, moisture regime, stress exposure, root system development, and the functional state of the turf surface. The framework links manageable agronomic factors with carbon inputs and losses in sand soil profiles

characterized by accelerated turnover and provides a mechanistic explanation for differences in long-term soil carbon trajectories under apparently similar visual and functional turf quality.

2. It has been established that moisture dynamics in sand-based profiles are characterized by a narrow operational range, including an upper plateau controlled by the drainage properties of the profile and a zone of increased instability under moisture depletion. Through explainable analysis (SHAP), a physically consistent hierarchy of factors has been confirmed, in which current soil volumetric water content (VWC) and evapotranspirational demand (ET_c) dominate short-term dynamics and exhibit threshold-like behavior. The results justify the discretization of VWC, ET_c into interpretable management states applicable in decision modeling and knowledge transfer among greens with similar hydraulic characteristics of the root zone.

3. It has been demonstrated that spatial moisture heterogeneity within a green substantially determines actual exposure to water stress and cannot be adequately described solely by mean VWC values. Indicators of uniformity and variation (DU, CV), area shares by moisture classes, and time-series clustering allow identification of persistent dry and wet zones and assessment of their seasonal stability. On this basis, the necessity of incorporating spatial diagnostics as an independent management layer - distinct from temporal depletion - recovery dynamics - is substantiated.

4. Predictable seasonal trajectories of root system development and stable treatment hierarchies under different irrigation regimes have been described. Deficit-oriented irrigation has been shown to stimulate the formation of a deeper and functionally more resilient root system, particularly under heat stress conditions. Predictive models indicate that water balance is the leading determinant of variations in root length, while aboveground spectral indicators provide complementary physiological information. Thus, a link is established between irrigation regime, nutrient dynamics, and belowground biomass distribution in the context of carbon resilience.

5. A high-precision semantic segmentation module based on a U-Net architecture has been developed, standardizing areas of interest (AOIs) and eliminating contamination in time series of vegetation indices. This ensures methodological consistency in long-term monitoring of heterogeneous imagery. Through multi-season clustering, large archives of vegetation indices have been reduced to stable and interpretable functional regimes of the turf surface, while similarity analysis identifies stable index groups associated with vegetation structure and stress status.

6. A reproducible method for constructing a Bayesian Network Decision Support System (BN-DSS) has been developed and validated, structured according to a priority model and adapted through updating with site-specific data. The network has been validated with independent datasets and provides a quantitative assessment of probabilistic reliability. The approach integrates moisture, nitrogen supply, turf surface condition, and root constraints into a unified probabilistic decision logic, explicitly addressing management trade-offs under uncertainty.

Applied Scientific Contributions

1. An integrated scientific-applied framework for carbon-aware and risk-oriented management of sand-based putting greens has been proposed. A formalized decision logic has been developed based on threshold states of soil moisture, evapotranspirational demand, root system condition, and spatial heterogeneity.

2. Irrigation planning rules based on threshold values of volumetric water content (VWC) and evapotranspiration (ET) have been formulated, enabling a balance between stress minimization and improved resource efficiency.

3. A methodology for spatial moisture diagnostics within a green has been developed, based on uniformity indicators (DU), variation (CV), moisture classes, and time-series clustering. This approach distinguishes temporal from spatial effects and supports more precise identification of causes of irrigation non-uniformity.

4. An approach for predicting the risk of root mass loss has been introduced through seasonal rooting models and regime-specific predictors, providing an early indication of critical periods, especially under heat stress. This allows adaptation of irrigation thresholds and definition of safe nitrogen fertilization limits according to actual uptake capacity.

5. A compact, interpretable set of vegetation indices for routine monitoring and DSS integration has been proposed, combined with standardized AOI masks for turf areas, ensuring a reliable evidence stream for assessing stress and the functional condition of the turf surface.

6. The developed BN-oriented DSS transforms empirical data into a formalized probabilistic decision-making framework through integration of sensor and spectral indicators, uncertainty management, and alternative scenario analysis. Through counterfactual evaluation, the system enables quantitative comparison of irrigation and fertilization strategies and enhances the transparency and justification of management decisions.

Scientific Contribution for Practical Implementation

A modular dashboard has been developed for the implementation of an intelligent BN-DSS, translating model thresholds into operational decisions on a daily-to-weekly scale. It integrates meteorological, sensor, and remote sensing data and provides harmonized interpretations for irrigation, fertilization, root development, and turf surface condition. As a practical tool, the dashboard supports diagnostics, planning, and a verifiable action log, ensuring a coherent interface for adaptive and carbon-aware management.

7. Critical Remarks and Questions

I have no critical questions or remarks regarding the submitted dissertation, which is well structured, methodologically sound, and presents clearly justified results.

The abbreviations used in the dissertation should be described separately.

8. Published Articles and Citations

The doctoral candidate has presented three articles related to the dissertation thesis - two single-authored and one co-authored, thereby meeting the minimum scientometric requirements of 30 points in accordance with the Regulations for the Implementation of the Law of the Development of Academic Staff in the Republic of Bulgaria.

The submitted abstract accurately reflects the structure and content of the dissertation.

CONCLUSION

Based on the various research methods learned and applied by the doctoral candidate, the properly conducted experiments, and the summaries and conclusions drawn, I consider that the submitted dissertation meets the requirements of the Law of the Development of Academic Staff in the Republic of Bulgaria and the Regulations of the Agricultural University for its implementation, which gives me grounds to evaluate it positively.

I respectfully propose that the esteemed Scientific Jury also vote positively and award Ivellin Dimitrov Markov the educational and scientific degree of "Doctor" in the scientific specialty "Forage Production and Grassland Management."

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Plovdiv

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