

Nitrogenius 2: A web-based decision support system for nitrogen governance and learning

B.T. Bariş^{a,*}, A. Hensen^b, G. Breeman^c, J.W. Erisman^a

^a Institute of Environmental Sciences, Leiden University, the Netherlands

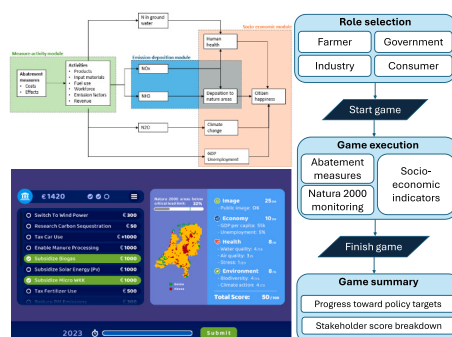
^b Netherlands Organization for Applied Scientific Research (TNO), The Hague, the Netherlands

^c Institute of Governance and Global Affairs, Leiden University, the Netherlands

HIGHLIGHTS

- We present a web-based interactive environment for nitrogen management.
- It integrates emissions, deposition, and socio-economic indicators.
- It includes a 1520-grid spatial nitrogen deposition model of the Netherlands.
- The system combines decision support and serious gaming functions.
- It enables stakeholder learning and structured policy trade-off analysis.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The Netherlands faces an acute nitrogen governance challenge. Intensive agriculture and industry cause freshwater eutrophication, terrestrial acidification, and climate change, while most Natura 2000 areas exceed critical deposition thresholds. A key barrier is limited shared understanding of how nitrogen flows connect ecological, economic, and social processes.

OBJECTIVE: This paper presents the design and evaluation of Nitrogenius 2, a web-based decision support system and serious game that makes nitrogen system dynamics, trade-offs, and stakeholder interdependencies explicit and accessible.

METHODS: Nitrogenius 2 integrates activity-based emission accounting, spatially explicit deposition modelling across a 1520-cell grid of the Netherlands, and composite socio-economic indicators within a turn-based simulation covering 2025–2035, incorporating 137 policy measures across four stakeholder roles. Evaluations included a validation test against official Dutch reference data and a classroom deployment at two Dutch universities ($n = 52$), complemented by a comparative analysis of environmental-economic trade-offs.

RESULTS AND CONCLUSIONS: All modelled values fell within 3% of official reference values. Over 80% of participants agreed the system improved their understanding of stakeholder roles and policy complexity, though lower scores on emission-deposition items indicate scope for improving interface transparency. Comparative

* Corresponding author at: Van Steenis Building, Room B3.07, Einsteinweg 2, 2333 CC Leiden, the Netherlands.

E-mail addresses: b.t.baris@cml.leidenuniv.nl (B.T. Bariş), arjan.hensen@tno.nl (A. Hensen), g.e.breeman@fgga.leidenuniv.nl (G. Breeman), j.w.erisman@cml.leidenuniv.nl (J.W. Erisman).

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analysis identified “Switch to Organic Dairy” as the most cost-effective agricultural measure, while targeted buyouts yielded the largest improvement in Natura 2000 protection.

SIGNIFICANCE: Nitrogenius 2 is an open-source platform bridging the analytical rigor of decision support systems with the participatory strengths of serious games. Its modular architecture supports adaptation to other geographic contexts and environmental policy domains.

1. Background

Nitrogen management in intensively farmed regions poses a multi-dimensional governance challenge, requiring trade-offs between environmental protection, agricultural production, and broader socio-economic objectives. Reactive nitrogen – i.e., all biologically active nitrogen compounds other than inert N_2 , including ammonia (NH_3), nitrogen oxides (NO_x), and nitrous oxide (N_2O) – use and production in the Netherlands is very high as the result of intensive agriculture and energy intensive society and industries (Kumar, 2021). This leads to a series of environmental impacts, including: (1) nitrate contamination of drinking water, (2) eutrophication of freshwater systems, (3) acidification and biodiversity impacts on terrestrial ecosystems and (4) global climate change induced by emissions of N_2O (Erismann et al., 2018). Abatement of nitrogen pollution has been on the political agenda for over 40 years with varying degrees of success (Erismann, 2021). One of the major challenges is navigating trade-offs between economic interests and ecological protection, where different stakeholders hold divergent views on what constitutes an acceptable resolution. Complicating factors for successful policies include the complexity of the nitrogen issue, the involvement and interests of many stakeholders, and cultural and societal aspects. The nitrogen issue resulted in an economic crisis in 2019 when the state council of the Netherlands rejected the latest nitrogen law, resulting in a situation where no new permits could be approved for any activity that resulted in an increase in N deposition in protected areas, affecting agriculture, but also all new construction activities (DutchNews.nl, 2020). The economic damage was estimated to be 28 billion euros during the 5 years after the verdict (FD.nl, 2022).

1.1. Nitrogen and EU regulations

The European Union's Birds Directive (2009/147/EC) and Habitats Directive (92/43/EEC) form the backbone of nature conservation across Europe. Together, these directives aim to protect and restore biodiversity by safeguarding wild bird species, natural habitats, and the rich variety of flora and fauna that define European ecosystems.

The Birds Directive focuses on the conservation of all wild bird species naturally occurring in the EU, prohibiting harmful activities and designating Special Protection Areas (SPAs) to ensure their survival. Meanwhile, the Habitats Directive extends protection to over 1000 species and 200 habitat types, establishing the Natura 2000 network, the world's largest coordinated network of protected areas. This network harmonizes conservation efforts with sustainable human activities to ensure that Europe's natural heritage thrives for future generations.

Under the EU Habitats Directive (Article 6), member states are required to take appropriate measures to avoid deterioration of Natura 2000 sites. In the Netherlands, this obligation has been translated into a nitrogen-specific legal framework that uses critical deposition loads as the primary metric for assessing site condition. Currently, a large portion of the Dutch Natura 2000 areas exceed these critical nitrogen deposition loads, indicating risks for biodiversity loss in (semi)-natural ecosystems (European Environment Agency, 2021). Addressing this exceedance is a Dutch policy priority that goes beyond the EU directive's general conservation requirements, as the Netherlands has adopted specific national targets for reducing nitrogen deposition on protected sites.

Since the 1980s, the Dutch government has implemented successive nitrogen reduction policies, primarily targeting ammonia emissions from agriculture and nitrogen oxide emissions from transport and

industry. These efforts led to a substantial reduction in national emissions between 1990 and 2000. After 2000, nitrogen deposition reduced slowly but remained far above the critical load thresholds (Compendium for the Living Environment, 2019). Several factors explain this policy standstill. First, the most cost-effective and technically straightforward measures have already been implemented. Second, post-World War II agricultural policy prioritized maximizing food production, embedding high-output farming systems into the economic structure. Third, food production is widely perceived, both by the public and by farmers, as a near-sacrosanct societal function, making structural reforms politically and socially sensitive. The persistence of the problem despite available scientific evidence highlights a disconnect between technical knowledge and policy action – a gap that different stakeholder groups perceive through different lenses, from environmental science and public health to economic viability and cultural identity.

Taken together, these factors explain why effective nitrogen abatement measures, which are often associated with reductions in agricultural production, are widely perceived as unacceptable. This structural resistance has significantly increased the complexity of nitrogen policymaking. Strong stakeholder opposition has hindered negotiations and intensified societal polarization, as illustrated by the large-scale protests organized by Dutch farmers in 2019 and 2022 against the government's nitrogen policies (Stokstad, 2019; DutchNews.nl, 2019, 2022).

Nitrogen governance involves multi-dimensional trade-offs, contested objectives, and fragmented decision contexts, making it difficult to explore policy consequences using conventional static models or single-indicator approaches. A central underlying challenge is limited system-level understanding of how nitrogen flows connect ecological, economic, and social processes. Stakeholders often engage with nitrogen policy from their own sectoral perspective, lacking an integrated view of how activities, emissions, deposition, and societal indicators interact. This gap in shared understanding hampers constructive dialogue and complicates informed engagement with policy measures. Interactive policy simulations can help by making system dynamics explicit and allowing stakeholders to explore how actions propagate through the nitrogen system (Demiray et al., 2024).

1.2. Role of serious games and introduction to Nitrogenius 2

Interactive simulations and serious games have increasingly been used in environmental governance to make complex system dynamics transparent and accessible to diverse stakeholders (Hardeveld et al., 2019; Haan et al., 2020; Edwards et al., 2019; Sari et al., 2024). By embedding process-based models within game environments, such tools allow users to explore trade-offs, feedback loops, and the consequences of alternative actions in a structured and risk-free setting (Steenbeek et al., 2020, 2021; Newell et al., 2021). They serve as boundary objects linking formal models to participatory processes, supporting scenario exploration, comparison of strategies, and structured deliberation among stakeholders (Voinov et al., 2015; Wamucii et al., 2025; Jean et al., 2018).

The original Nitrogenius game was a role-playing simulation developed in 2002, featuring an integrated model that simulates interactions across the nitrogen system (Erismann et al., 2002a). Since its creation, the game has been used extensively in both academic and stakeholder settings. Early evaluations showed that the game was effective in stimulating discussion and promoting understanding of nitrogen system complexity among policymakers and stakeholders (Erismann et al.,

2002b). A controlled evaluation demonstrated that the game provided a realistic representation of nitrogen dynamics, with in-game emission trajectories closely matching official Dutch data for the period 2000–2007 (Hensen et al., 2010).

Since the early 2000s, substantial changes have occurred in nitrogen policies, scientific understanding, stakeholder positions, and available abatement measures. In April 2020, the Dutch government introduced the Structural Nitrogen Program, aiming to bring 74% of nitrogen-sensitive hectares in Natura 2000 areas below critical deposition loads by 2035 (Ministry of Agriculture, Nature and Food Quality, 2020). These shifts in the policy and problem context prompted the development of a new and updated version of the original Nitrogenius system.

Nitrogenius 2 is a web-based decision support system implemented as a serious game, aimed at supporting both policy analysis and stakeholder learning in nitrogen governance. It embeds a simplified yet integrated representation of nitrogen emissions, economic activities, spatial deposition, and societal indicators within a role-based simulation. It enables policymakers, students, and other stakeholders to test policy interventions, assess their outcomes, and explore trade-offs in a controlled, risk-free setting. Beyond analysis, the system is explicitly designed as a learning tool for understanding nitrogen system dynamics, stakeholder interdependencies, and consequences of alternative strategies.

The aims of this paper are threefold: (1) to present the design, model structure, and functionality of Nitrogenius 2 as an integrated decision support and learning environment for nitrogen governance; (2) to evaluate the system's baseline accuracy against official Dutch reference data and assess its educational value through classroom deployment at two Dutch universities; and (3) to demonstrate its analytical capacity through a comparative analysis of 137 nitrogen reduction measures and their environmental-economic trade-offs within the model framework.

Publications on serious games and simulation models in environmental governance generally follow one of two structural approaches (Sari et al., 2024). In the first, the game or model is the primary result: design objectives are formulated, the development process described, and fitness-for-purpose evaluated. In the second, the game serves as a research method to investigate stakeholder behavior or policy outcomes (Edwards et al., 2019). This paper follows the first approach. The design, data integration, and model architecture of Nitrogenius 2 – including its spatially explicit deposition model, multi-stakeholder role system, and database of 137 policy measures – constitute the primary contribution. The exploratory evaluation in §3 provides an initial assessment of accuracy, usability, and educational potential. We recognize this evaluation covers only a subset of intended audiences; systematic testing with policymakers, farmers, and industry stakeholders is a natural next step.

Accordingly, this paper is structured around the system as its primary result. §2 describes the system scope, data sources, model logic, architectural components, and user interface. §3 presents the exploratory evaluation, including validation against official Dutch reference data, classroom deployment at two universities, and a comparative analysis of nitrogen reduction measures. §4 discusses the positioning of the system within the broader literature, its limitations, and implications for future use. §5 concludes with reflections and directions for further development and stakeholder engagement.

2. Nitrogenius 2 and its components

2.1. Scope and purpose

Nitrogenius 2 was developed to support the exploration of nitrogen reduction strategies under conflicting stakeholder objectives and to improve shared understanding of the system's complexity among diverse stakeholders.

Nitrogenius 2 is implemented as a turn-based serious game. Each turn represents one year, starting in 2025 and ending in 2035, reflecting the time horizon of current Dutch nitrogen policy targets. The system

can be used in both individual and group settings and allows users to assume the role of one of four stakeholders, each with their own responsibilities and interests:

- The farmer represents all agricultural activities and is responsible for most NH₃ emissions. They aim to increase agricultural production and maintain a positive public image.
- The industrialist represents 27 industries and is responsible for most NO_x emissions. They aim to increase industrial production and maintain a positive public image.
- The elected official represents the government and can enact laws that influence all other stakeholders. They aim for reelection and are therefore very concerned about their public image.
- The consumer represents the public and is responsible for household emissions. They aim to increase their happiness score – a composite model indicator derived from economy, public health, and environment sub-scores (see §2.3).

The game includes a multiplayer mode that operates through a lobby-based server system, allowing participants to connect from different devices via the internet. In group settings such as classrooms, workshops, or stakeholder meetings, multiple game sessions can be run in parallel by assigning participants into separate lobbies of four players. Each lobby functions as an independent game room, enabling simultaneous gameplay across multiple small groups.

The system has been applied in university courses and workshops with public administration, including the Dutch Ministry of Agriculture, Nature and Food Quality and several provincial governments. The game meets Mayer's (2009) requirements for games supporting policymaking: it integrates technical-physical complexity (the nitrogen model) and social-political complexity (stakeholder roles with competing objectives) within an interactive framework.

The system allows users to explore a wide range of nitrogen reduction measures, including agricultural, industrial, and consumption-related interventions. Measures can be tested individually or in combination, enabling users to compare their relative effectiveness, costs, and trade-offs. By disabling automated agents and events, users can also operate the system in a sandbox mode, in which they have control over all stakeholder roles and can systematically explore different policy configurations.

Nitrogenius 2 is not designed to identify optimal solutions, predict real-world outcomes, or prescribe policy choices. Instead, it supports exploratory and comparative analysis, allowing users to reflect on system behavior, stakeholder tensions, and consequences of alternative strategies under simplified but transparent assumptions. The system uses real Dutch data and geography because its primary use contexts – policy workshops with government officials and university courses on Dutch environmental governance – require recognizable inputs. However, outputs should be interpreted as indicative of relative system behavior, not as precise predictions. In organized sessions, participants compare outcomes, debate trade-offs, and identify areas of agreement or conflict – using simulation outputs as a shared evidence base rather than prescriptive guidance.

2.2. Data sources and model logic

Nitrogenius 2 integrates multiple data layers describing nitrogen-related activities, emissions, and environmental impacts in the Netherlands. These include sectoral production volumes from Central Bureau of Statistics of the Netherlands (CBS) and the Food and Agricultural Organization of the United Nations (FAOSTAT), nitrogen emission factors from NEMA (National Emissions Model for Agriculture), critical deposition load levels from AERIUS (a government-financed calculation instrument for the living environment), and policy-relevant socio-economic variables from CBS. The system incorporates a database of nitrogen reduction measures derived from

official Dutch policy documents, including the Structural Nitrogen Program. A detailed description of these sources and the methods with which the values were derived can be found in Tables 7 and 8 in Appendix C.

At its core, Nitrogenius 2 contains a fully integrated model that describes nitrogen flows and its environmental, social, and economic effects (see Fig. 1). The arrows in Fig. 1 express the relationships among measures and environmental, economic, and social variables, which are described in detail in the following sections. The game includes 137 policy measures distributed across the four stakeholder roles. This set is intended to be comprehensive with respect to measures proposed or implemented in the Netherlands. The only major omission concerns nature-inclusive farming measures, which were excluded due to insufficiently established or quantifiable nitrogen-reduction estimates in scientific and policy literature.

Each of the measures available to users have a list of effects that adjust certain variables in the activity module. Changes in these variables subsequently cause changes in nitrogen deposition levels, human health, and citizen happiness. Effects are applied annually, and cumulative impacts are tracked across the simulation timeline.

2.3. System architecture and design

Nitrogenius 2 follows a modular system architecture in which data management, emission accounting, spatial deposition, and indicator calculation are implemented as distinct but tightly coupled components. This allows individual elements to be updated without altering the overall model logic, while maintaining transparency in how decisions propagate through the system.

2.3.1. Activity-based data structure

At the core of the system is an activity-based representation of nitrogen-related economic sectors. Each economic activity (e.g., potato farming, dairy farming, steel production, private transport) is defined by a structured set of variables describing production, material inputs, emissions, employment, and costs (Appendix A).

For each activity, production is specified in physical or economic units (e.g., million liters of milk, kilotons of steel, million kilometers traveled), together with a corresponding product price per unit. Production volume and price determine the total production value of the activity. Activities may also require one or more input materials (e.g., artificial fertilizer, feed) and fuel (e.g., natural gas, electricity). All produced products, input materials, and fuel types are characterized by prices per unit and emission factors per unit. Baseline prices are derived from reference-year data and remain fixed across simulation turns unless altered by policy measures. The current version does not support user-defined price scenarios or exogenous price shocks (e.g., fertilizer price fluctuations due to geopolitical events). This is a recognized direction for future development.

Employment effects are represented through jobs per unit of production and associated salary levels, allowing total employment and personnel costs to be calculated consistently across activities. Total costs and profits are then derived from the combination of material costs and personnel costs relative to production value.

2.3.2. Emission calculation at the activity level

Nitrogen emissions are calculated explicitly at the activity level by combining production volumes and material and fuel inputs with pollutant-specific emission factors. For each activity, emissions of N_2O , NH_3 , NO_x , and NO_3 are computed as the sum of emissions from produced goods, raw materials, other materials, and fuel used in the production process.

Produced product emissions are calculated by multiplying the production volume of an activity by the corresponding emission factor for each nitrogen compound. Emissions associated with input materials are calculated in two steps. First, the total amount of a given input material (e.g., artificial fertilizer, fuel, or manure) used by an activity is determined by multiplying the activity's production volume by the material-specific input coefficient. Second, emissions from that material are calculated by multiplying the total amount of material used by its compound-specific emission factor. Where applicable, multiple input materials contribute additively to total emissions. Changes in

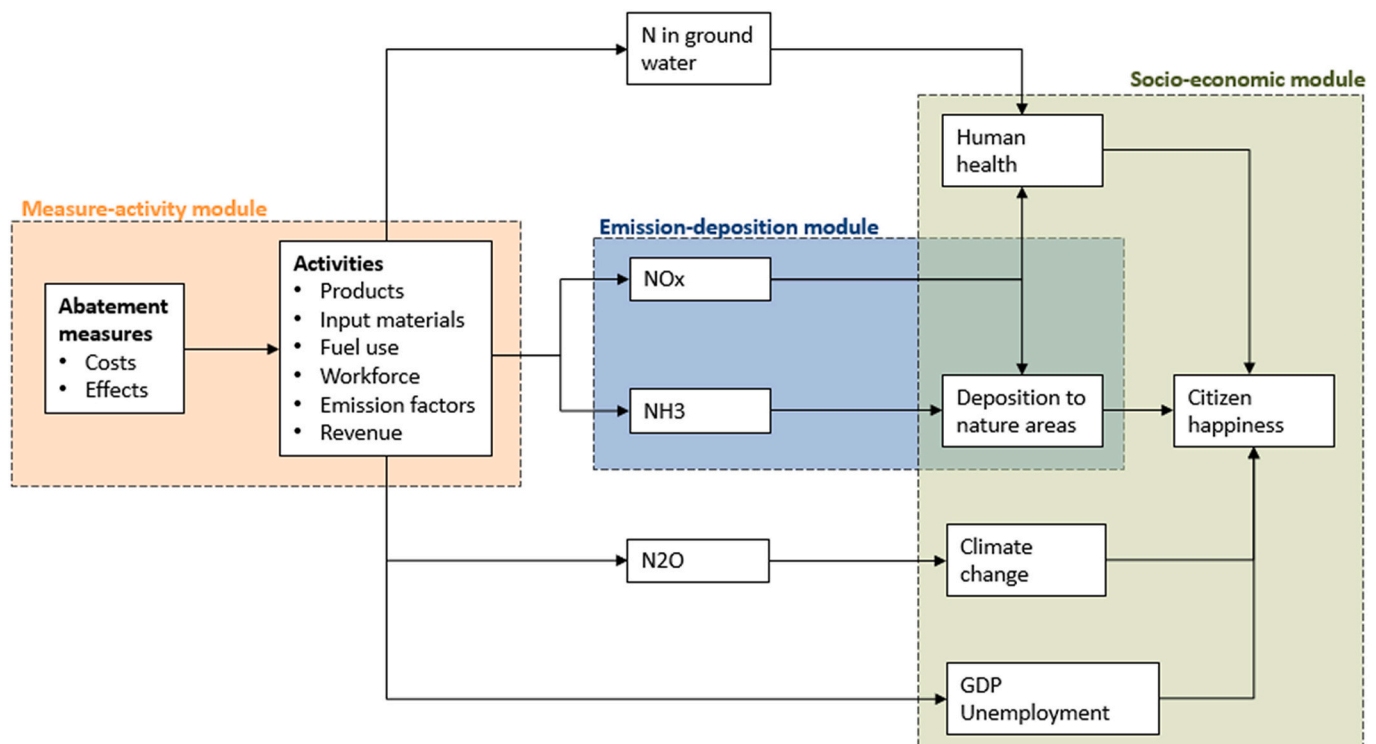


Fig. 1. Outline of the internal model of Nitrogenius 2.

production volume, input intensity, or emission factors thus directly translate into emission changes. All emission factors and input coefficients are derived from official Dutch data sources (NEMA, CBS) and are fixed during gameplay to ensure reproducibility and transparency. Because the system is open-source, these values can be updated when new data become available. All relationships are deterministic, supporting traceability but not capturing parameter uncertainty.

Measures influence these calculations by modifying one or more of the underlying variables. Some measures adjust production volumes directly (e.g., *Reduce Livestock Density*, *Increase Pork Production*), thereby scaling emissions, profits, and employment proportionally. Other measures alter technical coefficients; efficiency-related measures alter emission factors or material requirements (e.g., *Precision Fertilization* or *Green Stables*), reducing emissions per unit of output, whereas market-based measures (e.g., *Eat Less Beef*) affect product prices, indirectly influencing profitability and, consequently, stakeholder-relevant performance metrics (e.g., production value and profit in Appendix A).

2.3.3. Spatial emission allocation and deposition modelling

Once total emissions per activity have been calculated at the national level, they are spatially distributed across a 1520-grid (5×5 km) representation of the Netherlands. Spatial allocation uses predefined distribution coefficients specifying, for each activity, the fraction of its national emissions attributable to each grid cell. These coefficients are derived from spatially referenced data sources (e.g., land-use maps and industrial facility locations) and remain constant throughout the game unless modified by location-specific measures. When a measure changes total emissions from an activity, the change is distributed across grid cells proportionally to these baseline spatial coefficients.

The localized emissions of NO_x and NH_3 are subsequently translated into deposition using precomputed emission-deposition transfer functions, implemented as source-receptor matrices (SRMs). These matrices quantify how emissions in each grid cell (source) contribute to nitrogen deposition in all other grid cells (receptors). The SRMs account for atmospheric transport, compound-specific lifetimes, emission heights, and meteorological conditions. This approach follows established practice for calculating nitrogen deposition in the Netherlands (van Jaarsveld, 2004). Applying the SRMs to the spatial emission grid results in a spatially explicit representation of nitrogen deposition, including deposition in and around nitrogen-sensitive Natura 2000 areas.

This spatial methodology enables the system to capture regional differences in environmental pressure while maintaining computational efficiency and transparency. Rather than resolving detailed atmospheric chemistry, the model focuses on relative changes in deposition patterns resulting from user-selected measures.

2.3.4. Indicator calculation and aggregation

Environmental, economic, and social indicators are derived from the outputs of the activity and emission-deposition modules. Spatial calculations are limited to the deposition component: the SRM-based modelling produces grid-cell-level deposition values, which are then evaluated against site-specific critical loads to determine the percentage of nitrogen-sensitive Natura 2000 areas remaining below critical thresholds. All other indicators are calculated at the national level. Economic indicators (production values, employment, and stakeholder profits) are derived from the national activity accounts, while public health and environmental quality indicators are computed from national emission totals rather than from spatially resolved data.

These indicators are combined into composite factors with the weighing achieved using statistical normalization. The economy factor integrates gross domestic product (GDP) per capita and unemployment, the environment factor aggregates nitrogen deposition and greenhouse

gas emissions, and the public health factor combines air quality (proxied by NO_x emissions) and drinking water quality (proxied by NO_3 emissions). Citizen happiness is calculated as the sum of the economy, environment, and public health factors, yielding a normalized score ranging from 0 to 100. The detailed description of the citizen happiness calculation can be found in Appendix B.

By normalizing indicators within predefined ranges, the system emphasizes comparative changes over time and between scenarios rather than absolute values. This design choice supports interpretability and ensures that indicator responses remain bounded and consistent across simulation runs.

2.3.5. Modular integration and extensibility

The modular design of Nitrogenius 2 allows individual components, such as activity definitions, emission factors, spatial coefficients, or indicator formulas, to be updated independently as new data or policy measures become available. This architecture supports ongoing development and adaptation of the system while preserving the integrity of the overall modelling framework.

2.4. User interface and interaction workflow

Nitrogenius 2 was constructed using a game engine called Unity developed by Unity Technologies. All the game files including the source code are open-source and is accessible to and editable by the public through this link. Nitrogenius 2 is deployed as a web application that runs in a standard browser environment. The game is publicly available freely in two languages (English version: nitrogenius.polia.nl, Dutch version: nitrogenius-dutch.polia.nl).

Users interact with the system through an approachable, sleek graphical interface with few on-screen indicators. At the beginning of each turn, users review the current state of the system on the *Main Page* (Fig. 2), including environmental and other indicators that are relevant to the player's role, including role-specific indicators such as Public Image. The *Main Page* also serves as the primary decision interface, where users select their measures each turn.

Before gameplay begins, users are presented with an introductory page that provides background on the nitrogen crisis, followed by an instructions page that explains their assigned role and in-game objectives. Nitrogenius 2 can be played in single-player or multiplayer mode. In single-player mode, the other three stakeholder roles are controlled by automated agents that apply predefined strategies. In multiplayer mode, each role is assumed by a human participant; players do not directly observe one another's individual indicator results during gameplay, but all players share the same aggregate environmental and Natura 2000 outcomes, which respond to the combined choices of all participants. This shared outcome structure makes interdependence visible without requiring direct negotiation within the interface.

Just as is the discussion around the nitrogen crisis in the Netherlands, Nitrogenius 2 is centered around Natura 2000 areas. The percentage of Natura 2000 areas protected is constantly tracked on the right side of the *Main Page*. There is a bar that fills up as the user brings more areas back below the critical deposition load levels. The 74% mark is indicated on this bar. Below the bar, there is a color-coded map of the Netherlands that displays which Natura 2000 areas are protected. After the sixth turn (the year 2030), a message is displayed in the *Year Summary Page* (Fig. 3) that tells users whether they met the national target set for that year (50% by 2030).

The game ends after 2035 and a text is displayed in the *Game Summary Page* (Fig. 4) that states whether they reached the 74% target. During organized game sessions, the *Game Summary Page* is used to reflect on the outcomes attained by the players and facilitate discussion

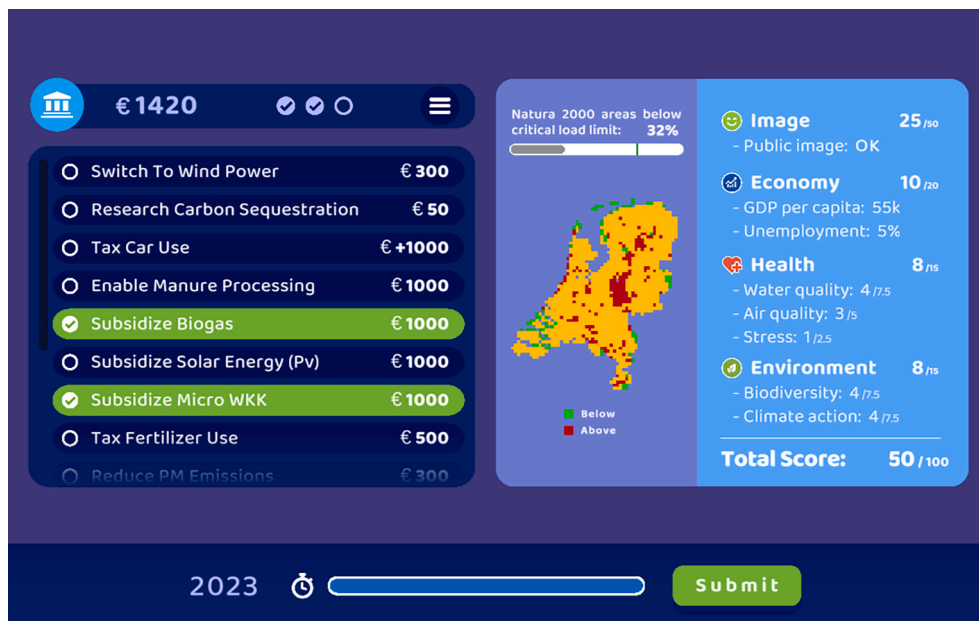


Fig. 2. Nitrogenius 2 main page (Government stakeholder's view).

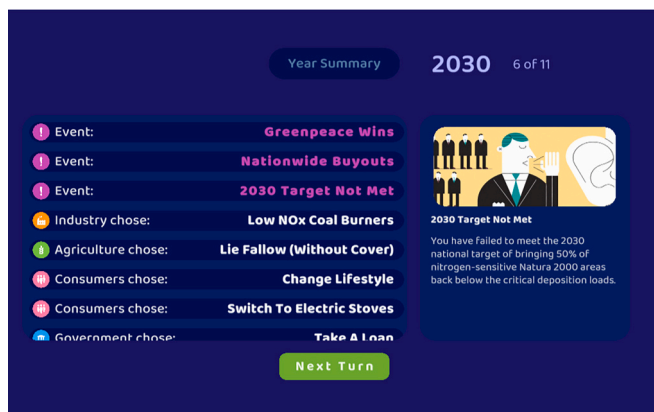


Fig. 3. Nitrogenius 2 year summary page.



Fig. 4. Nitrogenius 2 game summary page.

about the nitrogen crisis among players. In addition to automated agents, Nitrogenius 2 includes events that serve as another automated mechanism (visible in Fig. 3). Events are predefined occurrences (e.g., a livestock disease outbreak or a policy announcement) that are triggered

at specific turns and affect system variables independently of player choices, introducing contextual variability into the simulation. Both events and automated agents can be disabled to create a sandbox mode for systematic comparison of individual measures under controlled conditions.

3. Exploratory evaluation and testing

Two evaluations of Nitrogenius 2 were conducted to examine (1) baseline alignment with external reference values and (2) usability in a classroom deployment. In addition, a structured comparative analysis of individual measures was performed using the tool to explore their relative effects. Together, these assessments provide insight into the realism, interpretability, and comparative behavior of the system, while also highlighting its limitations.

3.1. Validation test

The applied validity test involved comparing critical design-produced values with real-world counterparts to ensure accuracy. These values include Natura 2000 surface area (as % of surface area of the Netherlands), percentage of Natura 2000 areas below the critical deposition load levels, and national NH_3 , NO_x , and N_2O emissions. The percentage differences between the design-produced values and the real-world values were all within a 3% margin (see Table 1), indicating a good agreement between the simulated outputs and observed data at the high level of aggregation.

3.2. Classroom deployment and user feedback

Nitrogenius 2 was introduced into the curriculums of two educational courses at two Dutch universities: a master's-level environmental policy course at Leiden University and a bachelor's-level environmental science course at University of Amsterdam. The course modules involved a hands-on workshop in which students, with backgrounds in environmental science, economics, and public policy, assumed the role of different stakeholders and played the game cooperatively using the networked multiplayer mode.

Following the sessions, participants completed a post-use questionnaire designed to evaluate the tool's educational value and capacity to

Table 1
Validation test results.

Variable	Value produced by Nitrogenius 2 at the start of the game (year 2025)	Real-world value	Difference	Real-world value source
Natura 2000 surface area (as % of surface area of the Netherlands)	14.3%	14.7%	−2.72%	Biodiversity Information System for Europe (n.d.)
Percentage of Natura 2000 areas below the critical deposition load (2016)	27.75%	28.5%	−2.63%	Compendium for the Living Environment (2019)
National NH ₃ emissions	124.4 kt	121.7 kt (2023)	+2.22%	Emissieregistratie (n.d.)
National NO _x emissions	283.5 kt	279.1 kt (2023)	+1.58%	Emissieregistratie (n.d.)
National N ₂ O emissions	21,571 kt	21,812 kt (2023)	−1.10%	Emissieregistratie (n.d.)

enhance understanding of nitrogen system complexity. The questionnaire focused on how well users felt they could interpret system outputs, understand stakeholder perspectives, and explore trade-offs between environmental, economic, and social outcomes. Responses were recorded using Likert-scale items and are reported descriptively.

Overall, participants reported positive experiences with the system's interface and interaction structure (Table 2). More than 80% of respondents agreed or strongly agreed that the system helped them understand differences between stakeholder roles and reflect on the complexity of real-world policymaking. A large majority (88%) also indicated that the system allowed them to experiment with different policy strategies and observe resulting changes in outcomes.

Lower scores were reported for items related to understanding the

Table 2
Summary of student evaluation results ($n = 52$). Items were scored on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). SD = standard deviation. Agree or strongly agree corresponds to scores of 4 or 5.

Statement	Mean	SD	% Agree or Strongly Agree
I have a better understanding of the different stakeholder roles involved in nitrogen policy.	4.12	0.73	83
The game helped me understand the trade-offs between economic, environmental, and social outcomes.	4.04	0.79	79
I can now better explain how different measures affect nitrogen emissions and deposition.	3.54	0.9	50
The spatial targeting of policies (e.g., Natura 2000 areas) became clearer through the game.	3.54	1.02	60
The game allowed me to experiment with different policy strategies and observe the outcomes.	4.19	0.86	88
Playing the game helped me reflect on the complexity of real-world policymaking.	4.06	0.85	79
The game provided insight into possible tensions or conflicts between stakeholders.	4	0.84	69
I would recommend the game as a tool for exploring environmental policy scenarios.	4.13	0.89	75

technical pathways through which measures affect emissions, deposition, and spatial targeting. Approximately half of respondents indicated improved ability to explain how measures influence emissions and deposition, and around 60% reported clearer understanding of spatial targeting related to Natura 2000 areas. This discrepancy warrants closer examination of the relationship between the game's mechanisms and its learning objectives. The high scores on stakeholder roles and policy complexity suggest that the role-based structure and turn-by-turn feedback effectively convey the multi-actor, multi-objective character of nitrogen governance. These outcomes appear robust because the game mechanics directly support them: players experience competing interests firsthand and observe how their choices interact with those of others. In contrast, the lower scores indicate that the interface does not make the causal chain from measure selection to spatially resolved deposition sufficiently transparent. Players can observe the aggregate effect of their choices on the Natura 2000 protection percentage, but the intermediate steps – which emission compounds are affected, how spatial redistribution works, and why certain areas respond more than others – remain largely implicit. The high scores thus reflect genuine learning about strategic and political dimensions, while the lower scores point to a specific interface limitation. Whether participants could critically assess unlisted measures depends on which understanding is considered: the experience of navigating trade-offs is transferable but understanding emission–deposition pathways would require additional features or debriefing. Improved in-game visualization of the emission–deposition chain is a priority for future development.

3.3. Comparative testing of measures

To complement the classroom deployment, a model-internal comparative analysis was conducted to examine how Nitrogenius 2 responds when individual nitrogen abatement measures are tested under identical baseline conditions. This analysis involved repeatedly running the model, with each of the 137 available measures applied individually and the system reset to initial conditions for each run. The script used to run the simulation can be found in the supplementary materials.

For each simulation run, changes in environmental outcomes (expressed as changes in the percentage of Natura 2000 areas below critical deposition load levels) were compared with changes in economic proxy indicators (GDP per capita and unemployment). These comparisons provide an exploratory indication of how different measures affect environmental outcomes relative to economic impacts within the model structure.

Based on these comparisons, measures were grouped into three broad categories: (1) measures that increase economic indicators at the expense of environmental outcomes, (2) measures that improve environmental outcomes while reducing economic indicators, and (3) measures that improve environmental outcomes with limited or no adverse economic effects. Examples in the third category include measures such as Precision Fertilization for the Farmer role, Solar Home Systems for the Consumer role, and Low-NO_x Engines (Ships) for the Industrialist role.

Within the second category, measures were ranked using a model-internal comparative ratio that relates changes in economic proxy indicators to improvements in Natura 2000 protection. Table 3 presents the ten measures with the strongest environmental improvements relative to economic impacts according to this metric.

An alternative approach to assessing cost-effectiveness is to evaluate the implementation cost per unit of environmental improvement, a metric that may be more relevant from a policymaking perspective. Table 4 presents the ten measures with the strongest environmental improvements relative to measure implementation cost. The more detailed versions of Tables 3 and 4 where effects on health, unemployment, stakeholder revenue, and other environmental factors can be found in Tables 9 and 10 in Appendix D.

This analysis is intended as an exploratory screening of measure behavior within the model rather than as a formal cost-effectiveness

Table 3

Nitrogenius 2: 10 most cost-effective measures (the cost-effectiveness column reflects the decrease in GDP for each unit of improvement in Natura 2000 areas).

Measure	Role	Implementation Cost (M€)	Δ GDP per capita (€)	Δ Natura 2000 (pp)	Cost-effectiveness (GDP/N2000)	Cost-effectiveness (Cost/N2000)
Switch to Organic Dairy	Agriculture	750	−1,54	0,38	−4,04	1973,684
Higher Tire Pressure	Consumer	500	−5,63	1,14	−4,93	438,5965
Choose Organic Beef	Consumer	0	−4,51	0,38	−11,86	0
Targeted Buyouts	Government	4000	−112,56	7,98	−14,1	501,2531
Choose Organic Pork	Consumer	0	−23,75	1,14	−20,82	0
Voluntary Buyout (Pork)	Agriculture	650	−27,59	1,14	−24,19	570,1754
Buyout Pig Farms	Government	2270	−11,04	0,38	−29,04	5973,684
Reduce Max Highway Speed	Government	1000	−74,75	2,28	−32,76	438,5965
Eat Less Beef	Consumer	0	−12,78	0,38	−33,61	0
Voluntary Buyout (Dairy)	Agriculture	2000	−64,32	1,9	−33,83	1052,632

Table 4

Nitrogenius 2: 10 most cost-effective measures (the cost-effectiveness column reflects the decrease in economic health for each unit of improvement in Natura 2000 areas).

Measure	Role	Implementation Cost (M€)	ΔGDP per capita (€)	Δ Natura 2000 (pp)	Cost-effectiveness (GDP/N2000)	Cost-effectiveness (Cost/N2000)
Eat Less Beef	Consumer	0	−10,34	0,38	−27,19	0
Increase Grazing Time	Agriculture	30	0	2,66	0	11,27
Introduce Ship Speed Limit	Government	50	1910,06	0,76	2511,72	65,75
Choose Organic Pork	Consumer	0	−9,96	1,14	−8,73	175,33
Install Catalysts (Petrol Cars)	Consumer	1000	0,77	5,7	0,14	175,33
Switch To Wind Power	Government	300	−6,63	1,14	−5,81	263
Choose Organic Chicken	Consumer	0	−11,85	0,38	−31,17	341,9
Reduce Max Highway Speed	Government	1000	−74,75	2,28	−32,77	438,33
Higher Tire Pressure	Consumer	500	−5,63	1,14	−4,94	438,33
Targeted Buyouts	Government	4000	−112,56	7,98	−14,1	500,95

assessment. The rankings depend on model assumptions, normalization ranges, and the use of simplified socio-economic proxy indicators. Therefore, the results should be interpreted as indicative of relative model behavior and trade-off patterns, not as prescriptive policy recommendations.

An important caveat concerns the interpretation of consumer-oriented measures such as Choose Organic Beef and Choose Organic Pork. In the model, these measures adjust the relative price per unit of organic versus conventional meat products, making organic farming more economically viable. This creates an interdependency between stakeholder roles: when consumers choose organic products, the farmer player can take advantage of the increased demand by converting to organic production, thereby reducing emissions while partially offsetting the economic cost of the transition. The pedagogical value of this mechanism lies in demonstrating how consumer choices can support agricultural sustainability transitions through market signals. However, it should be noted that Dutch agricultural products are largely traded on European and global commodity markets. The model does not capture these broader market dynamics, nor does it account for the possibility that shifts in domestic demand or production may be offset by trade flows within the EU. This is a deliberate simplification: Nitrogenius 2 operates at the national scale and prioritizes illustrating stakeholder interdependencies over modelling international trade.

More broadly, all available measures involve trade-offs that reflect the inherent complexity of nitrogen governance. For example, a full transition to organic agriculture would require substantially more land per unit of output due to lower yields, which under current dietary patterns is not feasible within national land constraints without reducing total production. Similarly, measures that reduce livestock density may improve environmental indicators domestically but can displace production to regions with less stringent environmental regulation. Nitrogenius 2 does not resolve these tensions but aims to make the domestic components of such trade-offs visible, thereby supporting informed discussion rather than prescribing solutions. Maintaining

political neutrality in this contested domain requires that the tool presents the consequences of choices transparently, without implying that any single pathway is without costs or constraints.

4. Discussion

Positioning Nitrogenius 2 within the broader literature, the system sits at the intersection of serious games and decision support systems (DSS). Serious games developed for policy contexts often overlap with DSS when they embed real data, formal models, and explicit decision tasks in interactive environments (Sermet et al., 2020; Ghodsvali et al., 2022; Gandziarowska-Ziolecka and Stasiak, 2019; Flood et al., 2018). These tools simulate real policy settings with goals, constraints, trade-offs, and feedback on decisions. In doing so, they perform core DSS functions such as scenario testing and structured comparison of alternatives (Sermet et al., 2020; Sajjadi et al., 2022; Zvirbule et al., 2025).

At the same time, serious games add elements that traditional DSS typically lack. Through role-play, negotiation, repeated rounds, and visible consequences, they support experiential learning, dialogue, and systems thinking (Czauderna and Budke, 2020; Haneklaus et al., 2025; Lin et al., 2022; Grund and Meier, 2016). Many serious policy games are used in stakeholder workshops or participatory settings to explore alternatives, deliberate on trade-offs, and co-create policy strategies. In these settings, they can directly inform real decision processes (Urcuqui-Bustamante et al., 2022; Ghodsvali et al., 2022; Flood et al., 2018). When this occurs, they effectively function as game-based or gamified DSS (Sermet et al., 2020; Fox et al., 2022).

Conventional DSS, by contrast, emphasize operational use in formal policy processes, traceable outputs, and integration with established data infrastructures. They often prioritize analytical rigor and transparency but provide fewer mechanisms for experiential engagement or structured dialogue (Roungas et al., 2020; Gandziarowska-Ziolecka and Stasiak, 2019). Nitrogenius 2 bridges these approaches. It embeds an integrated nitrogen model within a role-based decision-making

simulation while keeping assumptions, calculations, and outputs transparent. As a result, it combines the analytical comparability associated with DSS with the participatory and dialogical strengths of serious games. Through gameplay, participants explore scenarios, compare strategies, and observe quantified impacts grounded in real data and explicit model logic. In this way, Nitrogenius 2 exemplifies the functional overlap between serious games and DSS.

4.1. Credibility, salience, and legitimacy

A complementary way to assess tools on the science–policy interface (such as Nitrogenius 2) is to position them within the credibility, salience, and legitimacy framework (Cash et al., 2003). Credibility refers to the scientific adequacy of the information; salience to its relevance for the decisions users face; and legitimacy to whether the process is perceived as fair and respectful of divergent values. These attributes are not automatically mutually reinforcing – strengthening one can come at the expense of another (Cash et al., 2003; White et al., 2010). Serious games and simulation tools occupy an intermediate position between formal models and stories, combining quantified model logic with the engagement that narrative and role-play provide (van Noordwijk et al., 2020; Jean et al., 2018).

The principal strength of Nitrogenius 2 lies on the credibility side. The system embeds transparent and documented model logic, draws on official Dutch emission, deposition, and economic data, and reproduces reference trajectories in the validation test (§3.1). Salience – the relevance of the tool to the decisions users face – is supported to a degree by the tool's broad measure set: the 137 policy measures span the full range of intervention types that stakeholders encounter in Dutch nitrogen governance (see §4.2). Legitimacy is harder to secure: it depends on whose objectives and value weightings are embedded in the model, and is inherently contestable. What is legitimate for students may not be so for farmers or policymakers (White et al., 2010). Nitrogenius 2 attempts to address this challenge by assigning stakeholder-specific goals that often conflict with the overarching objective of achieving national environmental targets, requiring players to balance these competing priorities.

Two implications follow. First, Nitrogenius 2 sits toward the model end of the model–story continuum: its design emphasizes cognitive learning, while the affective and value-oriented dimensions associated with the story side are less developed (van Noordwijk et al., 2020). The role-based structure offers entry points for perspective-taking and surfacing divergent interests, which can foster empathy and dialogue in group play (Jean et al., 2018), but the tool does not yet incorporate explicit narrative or affective elements. Second, legitimacy is co-produced with users through framing, facilitation, and debriefing – it cannot be established by the artefact alone. Facilitators can strengthen legitimacy by making assumptions explicit and presenting outcomes as a basis for deliberation rather than as recommendations. Assessing these dimensions across different audiences is an important direction for future work.

4.2. Internalization of externalities

A related perspective is the five-level internalization framework of van Noordwijk et al. (2023). It distinguishes two categories of externalities absent from decision-making: those unknown to the decision-maker and those the decision-maker does not care about. For the first category, increasing awareness and understanding can help; for the second, deeper changes in values and relations are required. Internalization – literally ‘bringing into the inner spheres of decision-making’ – then proceeds through five levels: awareness-raising (I0), external compensation (I1), co-investment (I2), certification and standards (I3), and self-governance based on relational values of nature (I4). The framework explains why lower internalization levels, based on financial incentives alone, tend to be insufficient for lasting governance.

Nitrogenius 2 primarily supports awareness-raising (I0): by making visible how emissions, deposition, and socio-economic indicators respond to different measures, it addresses externalities that remain opaque because decision-makers lack an integrated system overview. The measures in the game span different levels – regulatory ceilings (I2–I3), buy-out schemes (I1), and voluntary technology adoption (I3–I4) – but the tool does not explicitly represent these distinctions. Nitrogenius 2 shows what the technical and economic consequences of measures are.

This is connected to the CSL assessment in §4.1. As van Noordwijk et al. (2023) note for the Dutch nitrogen debate, all five levels of internalization are simultaneously at play. Since Nitrogenius 2's measures span this full spectrum, the tool addresses the breadth of the policy landscape that stakeholders face – supporting its salience. The limitation is not in coverage but in representation: the tool shows what the consequences of measures are, not why stakeholders would adopt them. Incorporating stakeholder motivation discussions into facilitation protocols is one practical step; designing game mechanics that represent social dynamics of internalization more directly is a longer-term aspiration.

4.3. Outcome space, interactivity, and game character

The concepts of outcome space and solution space provide useful analytical vocabulary for serious games. The outcome space of a game comprises all possible results obtainable from the full set of player choices; the solution space is the subset of outcomes that satisfies externally defined targets or desirable conditions. Mapping these spaces helps characterize what a game can teach and where its design constrains the conclusions that players can reach.

In Nitrogenius 2, the outcome space is defined by 137 measures distributed across four stakeholder roles.

While some measures adjust production volumes directly, some alter technical coefficients (emission, price, material, or employment coefficients) during gameplay, representing the effects of management interventions, policies, and technology adoption. Because the coefficient structure is deterministic, the full outcome space is finite in principle. However, the combinatorial space is vast: measures can be applied in any order across ten annual turns, and since order and timing influence indicator trajectories through coefficient interactions, the number of distinct pathways is effectively unlimited – analogous to the number of ways a deck of cards can be arranged. The comparative analysis in §3.3 represents one non-temporal exploration of this space. The solution space, i.e., the subset of measure combinations that achieves a defined target such as bringing 74% of Natura 2000 ha below critical deposition loads by 2035, requires combining measures across multiple stakeholder roles rather than relying on any single intervention.

Several design features introduce path dependency and emergent dynamics. First, measure availability is dynamic: some measures can be applied only once, others have cooldown periods that prevent immediate reuse, and certain government subsidies reduce the cost of measures available to other stakeholder roles. The sequence of choices therefore shapes what options remain available and at what cost. Second, the game includes conditional events that respond to player actions. For example, when the governmental representative limits construction permits, a ‘Housing Crisis Intensifies’ event is triggered that decreases citizen happiness and forces the government to ease restrictions – a sequence modelled on the aftermath of the Dutch Council of State's 2019 ruling on the PAS (DutchNews.nl, 2020). Similarly, a ‘Greenpeace Files Lawsuit’ event fires automatically in 2027; the court outcome depends on whether the player is on track to meet the 50% nitrogen-reduction target by 2030, and a ruling in Greenpeace's favor mandates immediate government action – a scenario inspired by the Urgenda climate case. Third, in multiplayer mode four human players make simultaneous decisions each turn, and their choices jointly determine the trajectory of shared indicators. Since each player's optimal strategy depends on the

others' choices – which are not known in advance – the system becomes effectively non-deterministic from any individual player's perspective.

The game's outcome space is therefore best understood as technically finite but practically inexhaustible. In single-player mode, the principal value lies in structured exploration – comparing how different measure sequences and their timing affect the system's trajectory. In multiplayer mode, simultaneous decision-making by four players, conditional events, and measure interdependencies produce genuinely unpredictable pathways and support deliberation among stakeholders with competing interests. The game does not currently include mechanisms for formal negotiation, trading, or coalition formation; collective action, when it emerges, arises from discussion around the game rather than from within the game mechanics. Enriching these social interaction mechanics – through negotiation protocols, coalition structures, or more elaborate conditional events – is a direction for future development.

4.4. Social–ecological system perspective

Nitrogen governance can be understood as a social–ecological system (SES) challenge: technical solutions proposed within the ecological subsystem fail when they do not align with the rules, incentives, and behaviors of the social subsystem (Ostrom, 2009). Kirschke et al. (2019) demonstrate this for agricultural nitrogen pollution in Germany: the problem persists not because effective measures are unknown but because governance instruments lack the coherence to change behavior across actors. Tools supporting nitrogen governance must ultimately address both subsystems – biophysical nitrogen flows and the social processes that determine whether and how measures are adopted.

Nitrogenius 2 models the ecological–technical subsystem in considerable detail: emission sources, atmospheric transport, deposition on nature areas, and the effects of over 130 policy and management measures on these flows. The social subsystem, however, is represented only in stylized form. Players adopt stakeholder perspectives and select measures from role-specific portfolios, but the model does not represent the social dynamics that mediate adoption in practice. Political feasibility, institutional path dependencies, social norms, power asymmetries among actors, and the transaction costs of coordination are not captured by the current design. As a result, the tool can show what combinations of measures would achieve a given environmental target, but not whether those combinations are socially attainable or how actors might be motivated to pursue them.

This is connected to observations in the preceding subsections. The CSL assessment (§4.1) noted strength on credibility but limited reach into salience and legitimacy. The internalization framework (§4.2) concluded that the tool supports awareness-raising but does not model motivational processes behind adoption. The outcome space analysis (§4.3) identified limited inter-player interaction mechanics as a gap. All three observations point to the same underlying issue: the social subsystem of the nitrogen governance SES is underrepresented.

Two considerations temper this limitation. First, multiplayer mode and facilitated workshops introduce real social dynamics: participants negotiate and confront trade-offs in discussion, even though game mechanics do not enforce these interactions. The tool serves as a boundary object that makes the ecological subsystem legible, creating a foundation for deliberation alongside model outputs. Second, separating ecological modelling from social process is a deliberate choice at this stage. Accurately representing social dynamics requires empirical data and validated behavioral models not yet available at the needed specificity. Incorporating poorly grounded social assumptions could undermine the credibility that the tool currently offers. Future development should work toward fuller SES representation – e.g., agent-based adoption rules, institutional constraints, or scenario events that introduce governance dilemmas beyond the technical domain.

4.5. Limitations

The evaluations in this section reveal several limitations. First, although the model aligns well with reference data, it uses aggregated data and simplified relationships. This supports transparency and comparability, but the system is not designed to generate highly precise predictions.

Second, classroom feedback indicates that users need clearer explanations of how measures influence emissions, deposition, and final indicators. In its current form, some users find it difficult to trace this full cause-effect chain. Improving the visualizations and step-by-step explanation of these links would strengthen interpretability and learning outcomes.

Third, the classroom evaluation was conducted exclusively with university students in environmental science and policy programs. While students provide useful feedback on usability, interface clarity, and cognitive learning outcomes, their responses cannot be directly extrapolated to the intended primary audiences of policymakers, farmers, and industry representatives, who bring different prior knowledge, stakes, and expectations to the tool. As discussed in §4.1, the salience and legitimacy dimensions of the tool are audience-specific and have not yet been evaluated with these stakeholder groups. Systematic evaluation with professional stakeholders in workshop settings is planned as a next step and will follow a different research design focused on how the tool supports deliberation and perspective-taking in real governance contexts.

Fourth, positive feedback from educational use does not demonstrate that the tool provides decision automation for policymaking. Educational usability and policy robustness are different evaluation criteria. The comparative analysis of policy measures depends on the model structure and the chosen indicators. The results should therefore be interpreted as structured comparisons within the model framework, rather than as substitutes for detailed sector-specific or econometric analyses used in formal policy processes.

Despite these limitations, the exploratory evaluations and analysis provide useful insight into the system's behavior, usability, and potential role as an interactive decision-support environment for examining nitrogen governance challenges.

5. Conclusion

Nitrogen governance involves complex interactions between environmental pressures, economic activities, and societal objectives. Addressing these interactions requires tools that can make trade-offs explicit, support structured comparison of strategies, and enable stakeholders to engage with system dynamics over time. At the same time, gaps in understanding of the nitrogen system among policymakers, farmers, and the broader public can further complicate decision-making, underscoring the need for transparent and accessible modelling environments.

This paper presented Nitrogenius 2 as an integrated gaming and decision-support environment developed to meet this need. By combining multiple data layers, simplified system dynamics, spatial deposition modelling, and user-driven interaction, the system enables structured exploration of nitrogen management strategies under different policy configurations. At the same time, by embedding these dynamics within an accessible and role-based simulation, Nitrogenius 2 supports learning about stakeholder interdependencies and policy trade-offs.

Nitrogenius 2 is a transparent modelling environment that makes relationships among environmental, economic, and social indicators explicit. It allows users to trace how changes in production, technology, or behavior propagate through the nitrogen system. By structuring these

interdependencies within a consistent framework, the tool supports systematic comparison of measures and reflection on trade-offs. In this way, Nitrogenius 2 functions both as an analytical decision-support environment and as an educational platform for understanding governance complexity.

Evaluation results indicate that participants perceive improved understanding of stakeholder roles, trade-offs, and system interactions. Together with baseline validation, these findings support the credibility of the model while providing feedback for its ongoing refinement.

Several directions for future work are identified. First, the underlying data inventories and indicator sets can be extended to reflect new measures, updated emission factors, and all other greenhouse gas emissions. Second, additional interface features could be introduced to support different user needs, such as optional guidance layers or alternative indicator visualization methods. Third, the modular architecture of Nitrogenius 2 allows for adaptation to other geographic contexts or governance challenges, provided that appropriate geo-spatial data sources are available.

Future research could involve more targeted evaluation approaches, including comparative studies across user groups, longitudinal

deployments, or structured participatory settings. Such studies would allow a deeper examination of how interactive environmental modelling environments like Nitrogenius 2 are used in practice and how they may complement existing analytical tools in policy and educational contexts.

CRediT authorship contribution statement

B.T. Barış: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Hensen:** Resources, Data curation, Conceptualization. **G. Breeman:** Writing – review & editing, Supervision, Project administration. **J.W. Erisman:** Writing – review & editing, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Nitrogenius 2 activity examples

Table 5: Nitrogenius 2 activity examples (numbers in formulas refer to the indicator ID numbers in the first column).

	Potato farming	Private transport petrol car	Dairy farming	Steel industry
1 Sector	Agriculture	Traffic	Agriculture	Industry
2 NOx emission elevation	Low	Low	Low	High
3 Produced product	Potato	Travel km	Milk	Steel
4 Product volume	900	73,259	10,470	11,870
5 Product unit	Million Euro	Million km	Million liters	Kiloton steel
6 Product price per unit	1	0	0.4	0.22
7 Production value	(4*6)	(4*6)	(4*6)	(4*6)
8 Produced product N2O emission factor	0	0.067	0	0.025
9 Produced product NH3 emission factor	0	0.027	0	0
10 Produced product NOx emission factor	2.3	0.96	0.93	0.54
11 Produced product NO3 emission factor	0	0	0	0
12 Raw material type	Artificial fertilizer		Artificial fertilizer	
13 Raw material unit	Kiloton		Kiloton	
14 Raw material per unit	0.017		0.076	
15 Raw material total	(4*14)		(4*14)	
16 Raw material price per unit	0.76		0.76	
17 Raw material cost	(15*16)		(15*16)	
18 Raw material N2O emission factor	0.037		0.037	
19 Raw material NH3 emission factor	0.043		0.043	
20 Raw material NOx emission factor	0.027		0.027	
21 Raw material NO3 emission factor	0.043		0.043	
22 Other material type			Manure	
23 Other material unit			ton	
24 Other material per unit			0.000025	
25 Other material total			(4*24)	
26 Other material price per unit			50	
27 Other material cost			(24*26)	
28 Other material N2O emission factor			0	
29 Other material NH3 emission factor			211.61	
30 Other material NOx emission factor			0	
31 Other material NO3 emission factor			106.64	
32 Jobs per unit	5.55		6.58	1.31
33 Salary per job	24,600		24,600	30,000
34 Total jobs	(4*32)		(4*32)	(4*32)
35 Personnel cost	(33*34)		(33*34)	(33*34)
36 Total cost	(17 + 27 + 35)	(17 + 27 + 35)	(17 + 27 + 35)	(17 + 27 + 35)
37 Profit	(7 – 36)	(7 – 36)	(7 – 36)	(7 – 36)
38 Total N2O emissions	((4*8) + (15*18) + (25*28))	((4*8) + (15*18) + (25*28))	((4*8) + (15*18) + (25*28))	((4*8) + (15*18) + (25*28))
39 Total NH3 emissions	((4*9) + (15*19) + (25*29))	((4*9) + (15*19) + (25*29))	((4*9) + (15*19) + (25*29))	((4*9) + (15*19) + (25*29))
40 Total NOx emissions	((4*10) + (15*20) + (25*30))	((4*10) + (15*20) + (25*30))	((4*10) + (15*20) + (25*30))	((4*10) + (15*20) + (25*30))
41 Total NO3 emissions	((4*11) + (15*21) + (25*31))	((4*11) + (15*21) + (25*31))	((4*11) + (15*21) + (25*31))	((4*11) + (15*21) + (25*31))

Appendix B. Nitrogenius 2 sociological sub-model formulas

Table 6: Nitrogenius 2 sociological sub-model construction methodology.

Component	Range	Formula
Economy factor	0–30	$\left(\frac{GDP\ per\ capita_{max} - GDP\ per\ capita_{min}}{GDP\ per\ capita_{max} - GDP\ per\ capita_{min}} * (15 - 0) + 0 \right) + \left(\frac{unemployment_{min} - unemployment_{max}}{unemployment_{max} - unemployment_{min}} * (15 - 0) + 15 \right)$
Environment factor	0–30	$\left(\frac{mean\ NOx\ deposition_{min} - mean\ NOx\ deposition_{max}}{mean\ NOx\ deposition_{max} - mean\ NOx\ deposition_{min}} * (10 - 0) + 10 \right) + \left(\frac{mean\ N2000\ deposition_{min} - mean\ N2000\ deposition_{max}}{mean\ N2000\ deposition_{max} - mean\ N2000\ deposition_{min}} * (10 - 0) + 10 \right) + \left(\frac{national\ N2O\ emissions_{min} - national\ N2O\ emissions_{max}}{national\ N2O\ emissions_{max} - national\ N2O\ emissions_{min}} * (10 - 0) + 10 \right)$
Public health factor	0–40	$\left(\frac{mean\ NOx\ deposition_{min} - mean\ NOx\ deposition_{max}}{mean\ NOx\ deposition_{max} - mean\ NOx\ deposition_{min}} * (15 - 0) + 15 \right) + \left(\frac{mean\ NH3\ deposition_{min} - mean\ NH3\ deposition_{max}}{mean\ NH3\ deposition_{max} - mean\ NH3\ deposition_{min}} * (15 - 0) + 15 \right) + \left(\frac{environment\ factor_{max} - environment\ factor_{min}}{environment\ factor_{max} - environment\ factor_{min}} * (5 - 0) + 0 \right) + \left(\frac{economy\ factor_{max} - economy\ factor_{min}}{economy\ factor_{max} - economy\ factor_{min}} * (5 - 0) + 0 \right)$
Citizen happiness	0–100	$economy\ factor + environment\ factor + public\ health\ factor$

Appendix C. Data sources and processing

Table 7: Data collection methods.

Value	Economic activity	Source	Method
Product volume	Government	CBS (2025a)	$\frac{(GDP/100) * total\ government\ expenditure}{price\ per\ unit_{activity}}$
	Building construction, building materials	CBS (2025b)	$\frac{input\ price\ indice_{activity} * product\ volume_{activity}}{100}$
	Private transport petrol, private transport diesel, private transport gas, gas heating, gas cooking, domestic electric, private transport ships	CBS (2025a)	$\frac{total\ household\ consumption}{product\ volume_{activity}}$
	Beef farms, chicken farms, pig farms, dairy farms, hen egg farms, wheat farms, corn farms, potato farms, beet farms	FAO (n.d.-a)	$\frac{price\ per\ unit_{activity}}{value_{activity}}$
	Horticulture	CBS (2025c)	$product\ volume / \left(\frac{horticulture\ farms_{2000}}{horticulture\ farms_{2022}} \right)$
	Oil & gas, coal e-generation, gas e-generation, hydrogen e-generation, renewables, diesel industry	CBS (2025d)	$energy\ supply_{activity}$
	Chemical industry, steel industry	CBS (2025e)	$\frac{input\ price\ indice_{activity} * product\ volume_{activity}}{100}$
	Trade & services	CBS (2025f, 2025g)	$retail\ trade_{turnover} + value\ added_{current\ prices}$
	Fertilizer Industry, other crops	CBS (2025h)	$\frac{balance\ of\ trade_{activity}}{price\ per\ unit_{activity}}$
	All other economic activities	CBS (2025a)	$\frac{nonfinancial\ corporations\ gross\ value\ added}{product\ volume_{activity} / price\ per\ unit_{activity}}$
Electricity per unit	All economic activities	CBS (2025d)	$\frac{total\ energy\ consumption_{electricity}}{total\ electricity\ consumption_{activity}}$
Raw materials per unit	Agricultural activities that use fertilizer	FAO (n.d.-b)	$\frac{value}{total\ raw\ materials\ consumption_{activity}}$
	Agricultural activities that use animal feed	Knowledge Sourcing Intelligence (2022)	$\frac{product\ volume_{activity} * animal\ feed\ total\ market\ value}{total\ raw\ materials\ cost_{activity}}$
Other materials per unit	All agricultural activities	FAO (n.d.-c)	$\frac{price\ per\ unit_{animal\ feed}}{total\ value}$
Critical deposition load levels	NA	Kadaster (n.d.)	NA

Table 8: Implementation of Structural Nitrogen Program measures.

Measure	Cost	Effect
Buyout Pig Farms	2275	Decreases the product volume of pig farms by 3.86%
Targeted Buyouts	3500	Decreases the product volume of dairy farms, beef farms, chicken farms, hen egg farms, pig farms by 6.18%
National Buyouts	10,000	Decreases the product volume of dairy farms, beef farms, chicken farms, hen egg farms, pig farms by 2.84%
Adjust Animal Feed	725	Decreases the NH ₃ emission factor of raw milk, beef, chicken, hen egg, pork products by 7.53%
Increase Outdoor Grazing	30	Decreases the NH ₃ emission factor of raw milk and beef products by 0.39%
Dilute Manure	1050	Decreases the NH ₃ emission factor of raw milk, beef, chicken, hen egg, pork products by 1.28%
Green Stables	2800	Decreases the NH ₃ emission factor of raw milk, beef, chicken, hen egg, pork products by 6.2%

Appendix D. Detailed cost-effectiveness result tables

Table 9: Nitrogenius 2: 10 most cost-effective measures (the cost-effectiveness column reflects the decrease in GDP for each unit of improvement in Natura 2000 areas).

Measure	Switch to Organic Dairy	Higher Tire Pressure	Choose Organic Beef	Targeted Buyouts	Choose Organic Pork	Voluntary Buyout (Pork)	Buyout Pig Farms	Reduce Max Highway Speed	Eat Less Beef	Voluntary Buyout (Dairy)
Role	Agriculture	Consumer	Consumer	Government	Consumer	Agriculture	Government	Government	Consumer	Agriculture
Implementation Cost (M€)	750	500	0	4000	0	650	2270	1000	0	2000
Δ GDP per capita (€)	−1,54	−5,63	−4,51	−112,56	−23,75	−27,59	−11,04	−74,75	−12,78	−64,32
Δ Natura 2000 (pp)	0,38	1,14	0,38	7,98	1,14	1,14	0,38	2,28	0,38	1,9
Δ Health Factor	0,63	0,57	0,62	9,19	1,45	0,57	0,57	2,11	0,63	14,12
Δ Environment Factor	0,31	1,55	0,31	6,54	0,93	0,31	0,31	1,87	0,31	4,36
Δ Industry Revenue	0	0	0	0	0	0	0	−434,3	0	0
Δ Farmer Revenue	−20	0	10	−1465,8	−129,7	−40	−40	0	−134,6	−2189,2
Δ unemployment	−0,0011	0	0,0008	0	−0,0013	−0,0003	−0,0003	0	−0,0009	−0,0382
Cost-effectiveness (GDP/N2000)	−4,04	−4,93	−11,86	−14,1	−20,82	−24,19	−29,04	−32,76	−33,61	−33,83
Cost-effectiveness (Cost/N2000)	1973,684	438,5965	0	501,2531	0	570,1754	5973,684	438,5965	0	1052,632

Table 10: Nitrogenius 2: 10 most cost-effective measures (the cost-effectiveness column reflects the measure implementation cost for each unit of improvement in Natura 2000 areas).

Measure	Eat Less Beef	Increase Grazing Time	Introduce Ship Speed Limit	Choose Organic Pork	Install Catalysts (Petrol Cars)	Switch To Wind Power	Choose Organic Chicken	Reduce Max Highway Speed	Higher Tire Pressure	Targeted Buyouts
Role	Consumer	Agriculture	Government	Consumer	Consumer	Government	Consumer	Government	Consumer	Government
Implementation Cost (M€)	0	30	50	0	1000	300	0	1000	500	4000
Δ GDP per capita (€)	−10,34	0	1910,06	−9,96	0,77	−6,63	−11,85	−74,75	−5,63	−112,56
Δ Natura 2000 (pp)	0,38	2,66	0,76	1,14	5,7	1,14	0,38	2,28	1,14	7,98
Δ Health Factor	0,63	5,84	0,11	1,45	3,55	0,79	0,68	2,11	0,57	9,19
Δ Environment Factor	0,31	2,18	0,49	0,93	3,82	0,94	0,31	1,87	1,55	6,54
Δ Industry Revenue	0	0	24,874,2	0	0	−86,4	0	−434,3	0	0
Δ Farmer Revenue	−134,6	0	0	−129,7	0	0	−154,3	0	0	−1465,8
Δ unemployment	−0,0009	−0,001	0,3087	−0,0013	0	0,0029	−0,0004	0	0	0
Cost-effectiveness (GDP/N2000)	−27,19	0	2511,72	−8,73	0,14	−5,81	−31,17	−32,77	−4,94	−14,1
Cost-effectiveness (Cost/N2000)	0	11,27	65,75	175,33	175,33	263	341,9	438,33	438,33	500,95

Data availability

Data will be made available on request.

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