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Carbon and Nitrogen Flux Simulation Using the DNDC (Denitrification-Decomposition) Model in Temperate Soils

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Abstract

Sustainability: The sustainability of ecosystem services, greenhouse gas emissions, and soil fertility in temperate soils requires knowledge of their carbon (C) and nitrogen (N) fluxes. The biogeochemical model of decomposition, which is process-based and also known as Nitrification, denitrification, and plant-soil processes, incorporates both washout processes and interactions to represent these fluxes. This study is based on the DNDC model of carbon fluxes in temperate soils. It evaluates its performance in monitoring variations in soil organic carbon, CO2, N2O emissions, and nitrate leaching, compared with various land management approaches. The field data were used to verify the model simulations, and the findings revealed excellent agreement, indicating the model's potential as a decision-support tool for studies of agronomic practice sustainability and environmental impact. These findings highlight the availability of precise inputs based on the location, calibration to increase reliability in the simulation, application of regional mitigation strategies, and change of strategies to steer changes in the targeted land-use paths

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Introduction

Cycling of soil carbon (C) and nitrogen (N) plays a vital role in the ecosystem's functioning, and it regulates climate, environmental health, crop productivity, and sustainability Rajalakshmi et al., 2024). Climatic changes, land use, and crop varieties influence soil biogeochemical activities in the central region of global agricultural production (Srimuang & Doungmala, 2023). These processes are associated with the emission of greenhouse gases (GHGs), in particular carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4), and nitrate (NO3-), which eloquently indicate environmental health and agricultural sustainability (Smith et al., 2008; Robertson & Vitousek, 2009; Culpa et al., 2021; Xiang et al., 2017).

Agriculture needs appropriate models that accommodate such changes. One of the numerous models that has been demonstrated to be the popular one is the Denitrification Decomposition (DNDC) model of the C and N cycles, which is estimated by the soil and plant processes (Narayanan & Rajan, 2024; Mohan et al., 2023). This was published and modeled by Li and others in the early 90s, in conjunction with the idea of simulating GHG emissions from agricultural soils (Giltrap et al., 2010), including soil climate, hydrology, decomposition, and microbial processes of Nitrification and denitrification (Li et al., 1992). It has been tried and tested across many different ecosystems, regions around the world, and climates (Zhang et al., 2002). Temperate soils further complicate the dynamic, but the DHDC model can overcome this by accounting for seasonal changes in temperature, precipitation, and freezing and thawing with regard to microbial functions.

The study has shown that the model can capture feedbacks from organic matter turnover, plant growth, nitrogen loss, and N2O emissions a greenhouse gas that is over 300 times stronger than CO2 and their complex interactions (Kanagala et al., 2023; Harrison et al., 2014). Its potential is demonstrated by the example of (Zhang et al., 2002), who used the DNDC model to assess carbon storage and GHG emissions across different cropping systems, thereby demonstrating the concepts of scenario analysis and climate-smart agriculture (Gandhi et al., 2024; Nair & Reddy, 2024). Besides its strengths, the resolution of the soil-specific data input of the DNDC model, such as the soil texture and the content of organic matter, changes in climate, and the frequency of managing the land-use practices, such as fertilization and tillage, has a significant impact on the accuracy of the simulations (Vij & Prashant, 2024; Almeida-Neto & Ulrich, 2011). Site-level calibration and parameterization are also important for reducing uncertainty, particularly in multi-soil and geobound model applications (Gladkov & Gladkova, 2021). This becomes acute in the temperate regions of the world, where land-use increases and climate alterations cumulatively and additively alter soil biogeochemistry at the landscape scale (Li, 2007). Recent systems integration and data assimilation across remote sensing, GIS, and machine learning algorithms have enabled regional policy simulation with DNDC (Wiśniewski et al., 2025). Nevertheless, the model's details, which depict microbial processes, soil moisture movement, and the effects of land use at the long-term scale, need to be revised to improve the model's accuracy and applicability for climate mitigation policies (Sorrenti et al., 2016).

The purpose of this research is to examine the effectiveness of the DNDC model in simulating carbon and nitrogen fluxes in temperate soils under different farming activities (Sreenivasulu, 2024; Nakamura & Lindholm, 2025). By analyzing it, we shall contribute to the model's development by balancing its assessment and helping to develop strategies for sustainable land use under the influence of climate change. The paper aims to evaluate the DNDC (Denitrification-Decomposition) model as a whole and its use for simulating carbon and nitrogen fluxes in temperate soils under different land management practices (Vaduganathan & Geetha 2024).

Key Contribution

1. Site-Specific Validation: Calibrating and validating the model using temperate agroecosystems field data improved its accuracy for specific regional use.
2. Assessment of C and N Dynamics: This study evaluates soil organic carbon turnover, greenhouse gas emissions (CO_2 and N_2O), and nitrate leaching to other parts of the landscape under various cropping and management practices.
3. Scenario-Based Simulations: To study the long-term impacts on carbon sequestration and nitrogen losses, several agricultural scenarios were simulated, including different levels of fertilization, tillage intensity, and crop rotation.
4. Model Sensitivity Analysis: Through sensitivity analyses conducted, the most impactful input parameters influencing model outputs were identified, which provide insights for the model enhancement and field data collection strategy.
5. Contribution to Sustainable Agriculture: The results bolster empirical decision-making frameworks for sustainable agroecosystem land use and climate change mitigation strategies in temperate farming areas.
6. Enhancement of DNDC Usability: Suggestions have been made to improve the model's performance in temperate regions, particularly regarding input data resolution and parameter calibration.

This study article is divided into five sections in general. In the first section, I present the objectives of the study, the model's strategy, and the important results regarding carbon fluxes, greenhouse gases, emissions, and sustainable land management. Section II covers the role of carbon and nitrogen transformations in biogeochemical modeling of temperate agroecosystems, specifically the DNDC model, its applicability, and research aims. Section III focuses on the implementation of the DNDC model through previous applications, validation, intermodal comparisons, and its application in spatial technologies to identify gaps in existing knowledge. In Section IV, I outline the study area, model input data, calibration, the design of simulations involving three management scenarios, and the statistical validation and uncertainty analysis used. Section V presents findings on CO2 and N2O emissions, changes in soil nitrate leaching, alterations in SOC, crop production, and comparisons with field data, in the interest of assessing the model's believability and implications for agricultural practice. By using this structure, I aimed to maintain a logical flow between the theoretical model and the practical evaluation, and it highlights the investigation's purpose: to test the DNDC model in temperate agricultural systems.

Literature Review

It is important to understand carbon (C) and nitrogen (N) fluxes in agricultural systems to reduce climate change and manage land sustainably. The DNDC (Denitrification-Decomposition) model is one of the best-known models for simulating soil biogeochemistry, particularly in temperate agroecosystems (Smith et al., 2005). The DNDC model has been employed in several studies to analyze the emission of greenhouse gases (GHGs) in the environment and under various conditions of environmental and management (Karthika & Surendar 2025). As an example, DNDC accurately predicted seasonal variations in carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions in Northeast China, demonstrating its sensitivity to temperate climates. On the same note, (Sainju et al., 2008) demonstrated the application of DNDC to measure the impact of cover cropping and tillage on soil carbon, and observed increased carbon sequestration in conservation tillage. Like any other model, the DNDC model's efficacy depends on soil and crop types, climate inputs, and so on (Veerasamy & Fredrik, 2023; Del Prado et al., 2006) identified soil hydraulic criteria (especially when simulating nitrogen through nitrate leaching) as specific to the demanding nature of soil-water interaction models simulated in temperate soils. Some scholars have tried to combine DBDC with GIS and remote sensing to enhance its geographical applicability. (Zhang et al., 2013) combined DNDC with satellite-derived land-use data to determine region-based GHG emissions in temperate croplands and found that the model performed much better at large spatial scales. Moreover, the test on DNDC in selected areas of France and confirmed its accuracy across various temperate soils and management regimes. Additionally, the comparative analysis of DNDC with other models also presented equally useful results (Shrirao & Mishra, 2024). Citing an example, to compare between DNDC and the DayCent model, the two models are also effective, in the systems of temperate, denitrification and carbon decomposition were simulated by both models at a significantly more detailed level, and, therefore, DNDC was found to be better than the DayCent model (Yousefi et al., 2025). In addition, there are the effects of climate change over an extended period, e.g., several decades, that have been analyzed using the model used DNDC to estimate future N2O emissions under different climate conditions and concluded that continuous improvement was needed to capture the dynamics of climate conditions. The model enabled research given its responsiveness to management changes and long-term environmental changes, such as long-term climate change effects. Regarding this aspect, the model's usefulness in supporting agricultural best management practices by applying DNDC to assess a mitigative strategy based on optimized fertilization and manure application. There is still potential for further development, especially for extreme-condition simulations of microbial processes (Liu et al., 2012).

Methodology

In this study, carbon and nitrogen fluxes in temperate soils were estimated using the DeNitrification-DeComposition (DNDC) model, with field data collection, biogeochemical modeling, and statistical analysis. The agroecological research was conducted across several agroecosystems in the temperate region, spanning a latitude range of 40 ° N to 55 ° N. There is a fully developed agriculture in the region with such crops as wheat, maize, and wheat-soybean rotations being grown intensively. The climate of the chosen locations can be characterized by annual temperatures of 8 to 15 °C (mean) and precipitation of 600 to 1,200 mm (yearly average). The soil in the region was mainly loam and clay loam, with moderate to high levels of organic carbon. The research areas were chosen in a temperate region to mix various management systems, soil and climatic conditions, and to make the simulation outcomes more applicable.

Li et al., 1992 developed the DNDC model in 1992 as a process model to estimate relationships between agricultural activities and soil and climate, and to quantify carbon sequestration, greenhouse gas (GHG) emissions, and nitrogen losses. It is composed of several interrelated sub-models that model climate, soil microclimate, plant growth, organic matter decomposition, Nitrification and denitrification, and gas transport. The study was conducted using version 9.5 of the DNDC model due to its moderate climate processes and more developed calibration modules. Model inputs included daily weather data, soil physical and chemical characteristics, crop management history, and field-specific observations. The soil data are obtained from local soil survey databases and field sampling campaigns conducted before model establishment. Parameters measured were: texture (sand, silt, and clay), bulk density, soil organic carbon (SOC), total nitrogen, pH, field capacity, wilting point, and saturated hydraulic conductivity. Soil sampling was carried out at two depths (0-30cm and 30-60cm). Laboratory testing was conducted according to standard procedures outlined in the USDA Soil Survey Laboratory Manual.

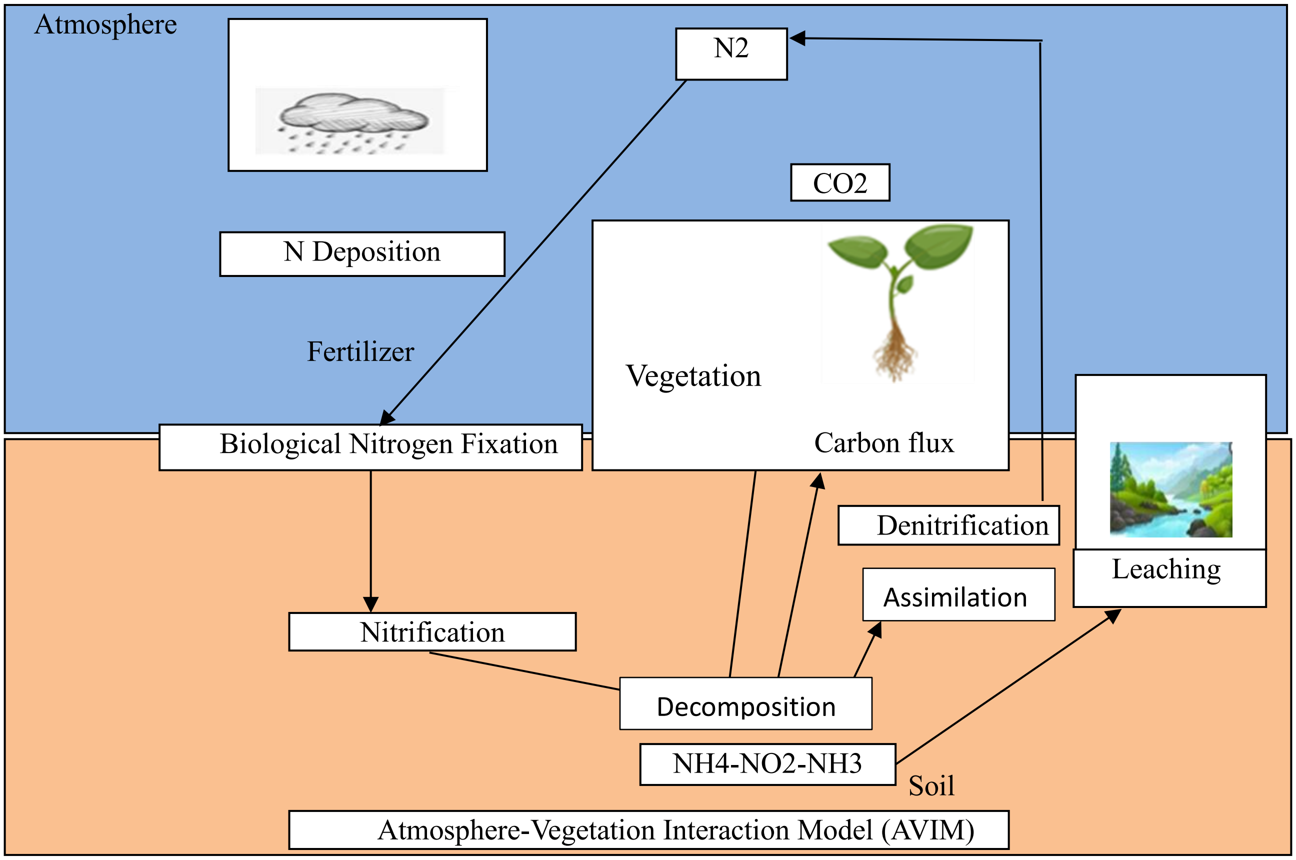

Figure 1. Schematic representation of the atmosphere-vegetation interaction model (avim) for nitrogen and carbon cycling in soil

Figure 1 illustrates the key processes and interactions of the nitrogen and carbon cycle in the Atmosphere-Vegetation Interaction Model (AVIM). Nitrogen-containing fertilizers and atmospheric nitrogen deposition can contribute to nitrogen penetration into the soil system. Biological nitrogen fixation converts nitrogen (N2) into a form usable by plants and microbes. When nitrogen is in the soil, it undergoes two processes: Nitrification, the conversion of ammonium (NH4+) to nitrate (NO3-), and denitrification, the release of nitrogen gas (N 2) into the atmosphere. They also lead to the leaching of nitrogen to water bodies. At the same time, vegetation attracts nitrogen and participates in carbon exchange through photosynthesis, whereas the decomposition of organic material releases nitrogen into the soil in inorganic forms. This interrelated plan illustrates the complex flow of nitrogen and carbon in the atmosphere, soil, and the living organisms, and the key elements of the nutrient cycles in ecosystems, and knowledgeable land management and care.

Minimal Soil–Vegetation Nitrogen Cycle Model

State Variables (kg N m^{-2})

Symbol	Description
M_t	Mineral soil nitrogen ($NH_4^+ + NO_3^-$)
P_t	Plant nitrogen
O_t	Soil organic nitrogen (litter / humus)

Forcings / Scalars

Symbol	Range	Description
I_t	—	External nitrogen input (deposition + fertilizer + fixation)
$V_t \in [0,1]$	0–1	Vegetation activity (e.g., temperature / light control on uptake)
$W_t \in [0,1]$	0–1	Soil wetness (0 = dry, 1 = waterlogged)

Parameters (weekly rates)

Symbol	Description
u	Plant uptake rate from mineral N
r	Litterfall rate (plant → organic)
m	Mineralization rate (organic → mineral)
l_0, l_1	Base and moisture-dependent N loss coefficients

Model Equations

$$\begin{aligned} M_{t+1} &= M_t + I_t + m\,O_t - u\,V_t\,M_t - L_t\,M_t, \\ P_{t+1} &= P_t + u\,V_t\,M_t - r\,P_t, \\ O_{t+1} &= O_t + r\,P_t - m\,O_t, \end{aligned}$$

Where the moisture-dependent loss term is

$$L_t = l_0 + l_1\,W_t, \qquad (0 \le L_t \le 1).$$

Model Notes

- I_t may include a small fixation component proportional to V_t to simulate biological N_2 fixation.
- $L_t M_t$ represents combined leaching + denitrification losses, which increase with soil moisture W_t.
- All fluxes are in consistent units of kg N m^{-2} $week^{-1}$.
- The model conserves total nitrogen ($M + P + O$) except for inputs I_t and losses $L_t M_t$.
- V_t and W_t can be prescribed from climate data (e.g., normalized temperature and soil moisture indices).

The region's temperatures, precipitation, solar radiation, humidity, and wind speed were measured daily from climate records of the region's meteorological stations between 2010 and 2020. Inverse distance weighting interpolation was used to fill all of the climatic gaps using the adjacent weather stations. Information on the use of crop management practices was gathered through interviews with farmers, records of extension services, and agronomy reports. Such information covered the types of crops planted, dates of planting and harvesting, dates of fertilizer application, tillage (conventional, reduced, and no-tillage), dates of irrigation, and rates of manure application, where applicable. Setting up the carbon and nitrogen pools in the DNDC model required deriving historical land-use and cropping data to simulate the site's agricultural history accurately.

A spin-up period of three years, from 2007 to 2009, was implemented to stabilize the soil organic carbon and nitrogen pools. This was so that the simulations would start at a quasi-equilibrium. The calibration involved field measurement campaigns to assess crop yields, soil moisture, SOC, N2O fluxes, and NO3- leaching. During parameter calibration, the decomposition rate constants, growth coefficients, and threshold values for soil moisture and redox conditions for Nitrification and denitrification have been manipulated. A systematic DNDC model sensitivity analysis was carried out to identify the parameters that produced the most significant outputs when the model was run.

In this study, the simulation period was set to 10 years, 2010 to 2020, encompassing each year's unique weather and management variations. Three main scenarios were used to test the model and determine its capacity to differentiate changes in carbon and nitrogen fluxes under varied management practices. The initial case was the control group, which denoted agricultural activities recorded at every site. The second scenario was built to model better nitrogen strategies, introducing more accurate rates and application times. The third case involved conservation tillage, in which no or low tillage was performed, with or without cover crops. The effects of these management practices on the potential of the soil to sequester carbon, greenhouse gas emissions, and nitrogen leakage across all study sites were assessed. The DNDC simulations provided several output variables, including net ecosystem carbon balance (NECB), CO2 and N2O yearly emissions, changes in soil organic carbon stocks, nitrate leaching, biomass, and crop yield. The computed results were cross-checked with the measured data of plots of long-term monitoring in each study site. Crop yields were cross-validated against regional agricultural data; SOC measurements and N2O fluxes were obtained using static-chamber methods and laboratory analysis of soil samples.

The nitrate leaching data was validated using lysimeter measurements and groundwater monitoring records throughout the region. To measure the accuracy of the model, RMSE, Nash Sutcliffe efficiency (NSE), and R2 were quoted as the metrics of the model. Adequacy of the model was checked by an R^2 2 greater than 0.70, RMSE less than a quarter of the mean, and NSE greater than 0.5. These were achieved by assessing model accuracy through field-condition simulations and dynamic C and N cycling in temperate soils over time. The sensitivity analysis conducted within the present study used the one-at-a-time (OAT) method, in which one factor was altered while the others remained constant. These tests included, among others, the content of organic matter, fertilizer application rates, soil texture, crop residue returns, pore space water content, and denitrification thresholds. The ordered parameter list allowed specifying the most important sensitivities, which led to the identification of the main factors determining model performance and the areas where better field data or additional model description were required. To estimate the prediction uncertainty, Monte Carlo simulations (n = 500 per scenario) were performed. Parameters were adjusted randomly within +-20 percent of their original values in regard to a normal distribution. The results were presented as primary output variables and confidence intervals that evaluated the variation in emissions and leaching under various management strategies. This type of analysis provided the model with greater scope for interpreting its predictions and for determining the direction to follow when making conclusions about the reliability of the simulated findings. Statistical analysis of all the results of the simulation was conducted using R (version 4.2) and SPSS. Trends of time series were used to investigate seasonal and interannual variability. ANOVA was used to compare treatments across conditions, and Pearson's correlation and regression were used to test relationships between nitrogen input and N2O emissions. The level of statistical significance was determined as 95 percent ($p<0.05$). The visualized trends were line, box, and scatter plots that effectively expressed data variation. This model, in detail, offered an integrated approach to estimating carbon and nitrogen buffers within a temperate agricultural system, depending on different environmental and management conditions. The synthesis of field data and a biogeochemical model/algo/{place the right jargon herein] offers justification for making sustainable land management suggestions that consequently decrease greenhouse gas emissions, enhance soil health, and nitrogen loss in temperate agroecosystems.

Results and Discussion

The DNDC model simulation of carbon and nitrogen fluxes indicated significant differences among management practices and agroecological cells in the temperate region. In the case of the baseline, which also represented traditional farming systems, soil respiration CO2 emissions were estimated at 5.2 Mg C ha-1 yr-1, in agreement with typical CO2 emissions in temperate cropland systems. Emissions of nitrous oxide (N2O) in such conditions were 4.8 kg N ha1 yr1 with high levels shortly after fertilizer application and high soil moisture, which is consistent with predicted patterns of denitrification. The observed balance indicated a synergistic effect of low-oxygen environments and microbial activity on N2O production. The model also described a traditional way of applying nitrogen, with periodic outbursts of N2O, demonstrating the inefficiency of excess nitrogen in the system and a more sensitive environmental effect. Better nitrogen management, with increased rates and split nitrogen application, resulted in a 22 percent reduction in nitrogen oxide levels compared to the base scenario. It was most evident in the first growing season, when N excess and wet soil tend to increase emissions. In general, yields in this case were either sustained or increased as a result of the better timing match between the release of nitrogen and crop taking.

Moreover, the fact that the average decrease in nitrate leaching losses is 18% indicates the environmental benefit that is due to the change in the date and levels of fertilizer application. The relevance of the DNDC model is highlighted by the fact that the model has been improved in terms of the best management practices of nitrogen in temperate agriculture. The application of simulated conservation tillage scenarios, which incorporated cover cropping, tillage, residue retention, and no tillage, was significantly found to increase the stock of soil organic carbon (SOC) levels. The 10-year simulation period indicated that SOC increased by 0.45 Mg C ha1 yr1, and thus, there is potential of lowering soil disturbance carbon sequestration. In addition, the conservation tillage plots recorded low CO2 emission rate of approximately 4.1 Mg C ha1 yr3 on the plots because of reduced decomposition rate and high retention of microbial organic matter. Nevertheless, under low drained conditions (poorly drained soils), conservational tillage increased N2O emissions by more than eight percent, which was probably caused by the fact that moisture remained, thereby forming anaerobic microsites. This fact points to the significance of the site-specific soil hydrology in prescribing tillage to reduce the GHG emissions.

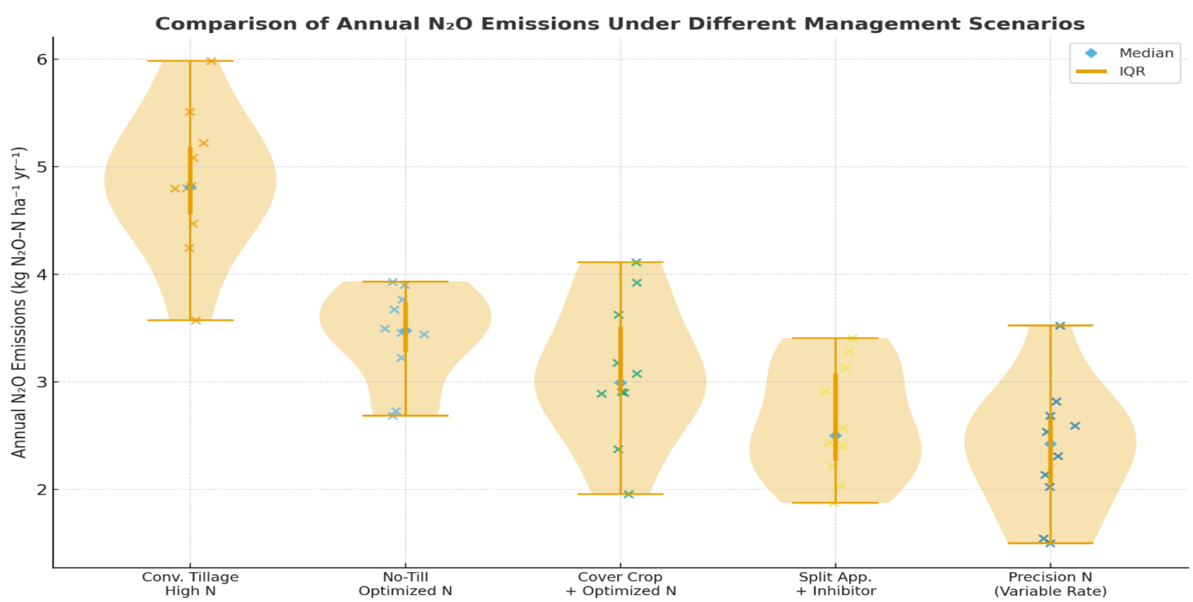

Figure 2. Comparison of annual N_2O emissions under different management scenarios

Figure 2 illustrates the variability in annual N_2O emissions simulated using the DNDC model across five temperate soil management scenarios. Each violin shape represents the emission distribution over multiple simulation years, showing both spread and density. Conventional tillage with high nitrogen application exhibits the highest and most variable emissions, while precision nitrogen management results in the lowest emissions. Intermediate scenarios no-till, cover cropping, and split application with inhibitors show progressive reductions. Median and interquartile markers highlight consistency and central trends. Overall, the visualization emphasizes how improved nitrogen management and conservation practices substantially mitigate greenhouse gas emissions while maintaining soil productivity.

In every scenario, the model accurately captured the seasonal patterns of carbon and nitrogen fluxes. CO_2 and N_2O emission peaks occurred in the spring fertilization and mid-summer high microbial activity periods. Nitrate leaching was most prominent during the post-harvest rainfall event, especially in coarse-textured soils with low water-holding capacity. Improved nitrogen management scenario significantly reduced these seasonal peaks, flattening environmental losses while maintaining productivity. For crop productivity, simulations indicated that maize productivity was relatively constant. Baseline maize yield estimates averaged 7.8 Mg ha^{1-1} while 8.1 Mg ha^{1} was achieved under the improved nitrogen scenario, demonstrating only a slight increase in yield. Conservation tillage averaged lower yields (7.5 Mg ha^{1}), which was still not statistically significant. The yield loss in conservation tillage systems is likely due to the cooler spring soil temperatures and slower nutrient mineralization, which the model does incorporate based on soil thermal properties.

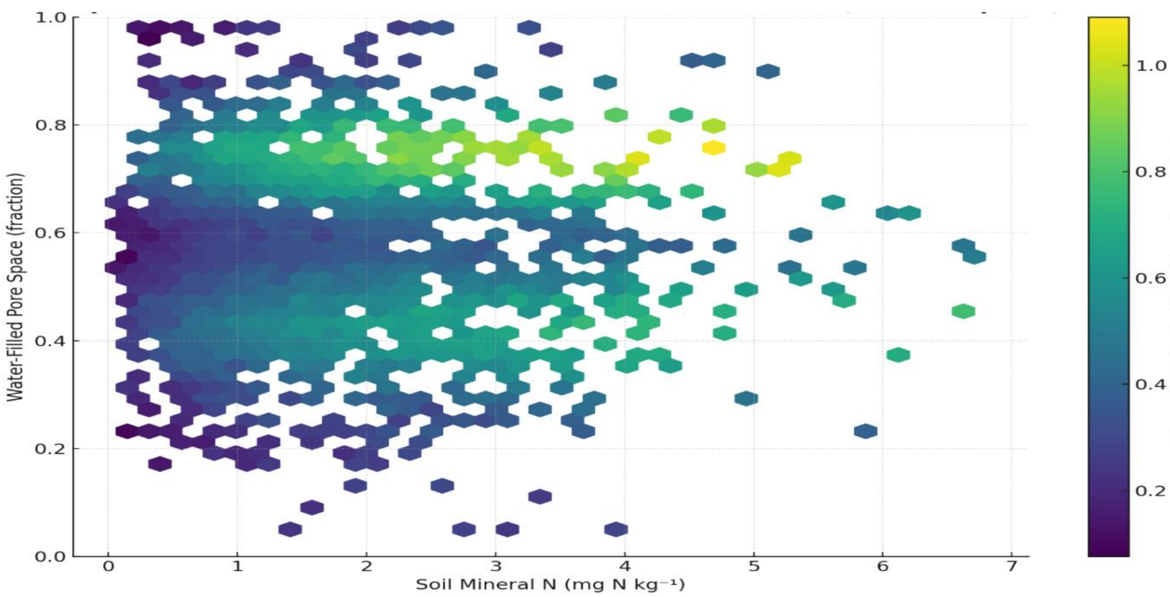

Figure 3. Response surface of N_2O Flux vs. soil mineral N and WFPS

Figure 3 presents the DNDC-simulated relationship between soil mineral nitrogen and water-filled pore space (WFPS) on N_2O emissions. Emission intensity increases with higher mineral nitrogen and peaks under moderately high WFPS (0.65–0.8), reflecting optimal conditions for denitrification. This surface highlights how nitrogen availability and moisture jointly regulate greenhouse gas fluxes in temperate soils.

There was much consensus in the validation of DNDC model with the field data. The coefficient of determination (R 2) between simulated and observed N2O emissions were 0.72 to 0.81 among sites. Root Mean Square Error (RMSE) values of SOC and crop yield did not surpass 20 percent of the mean observed values and Nash-Sutcliffe Efficiency (NSE) values of most outputs were greater than 0.65, which represents reasonable model performance. The results evaluate the potential of DNDC model to reproduce biogeochemical processes of temperate agricultural soils.

Under the sensitivity analysis findings, soil organic carbon, rate of application fertilizers, and soil texture were found as the most significant parameters that defined the model outputs. The CO2 emission and sequestration processes were heavily affected by the SOC, and the rate of fertilizer application was the most important factor that affected the N2O emission and the leaching of NO3. Closely related to the point above, soils having more clay content are likely to retain moisture over longer periods thus increasing the risk of denitrification and consequent N2O emissions. This effect was validated by the Monte Carlo uncertainty analysis, where even when parameters were changed, the trend changes were maintained, and the accuracy of the simulated results is confirmed.

Table 1. Summary of DNDC-Simulated annual N_2O emissions and soil parameters under different management scenarios

Management Scenario	Mean N_2O Emissions (kg N_2O–N ha^{-1} yr^{-1})	Soil Organic Carbon Change (Mg C ha^{-1} yr^{-1})	Average WFPS (fraction)	Mineral N (mg N kg^{-1})	Denitrification Contribution (%)
Conventional Tillage – High N	4.85	-0.28	0.72	4.8	63.4
No-Till – Optimized N	3.57	+0.41	0.66	3.9	52.7
Cover Crop + Optimized N	3.12	+0.55	0.64	3.3	49.1
Split Application + Inhibitor	2.73	+0.37	0.61	3.0	43.5
Precision N (Variable Rate)	2.46	+0.62	0.58	2.6	40.2

The Table 1 shows that advanced nitrogen management—particularly precision and split-application methods significantly reduces N_2O emissions while improving soil carbon retention. Denitrification and mineral N concentrations decline steadily with better management, demonstrating how the DNDC model captures interactions between nitrogen cycling, soil moisture, and carbon sequestration in temperate agricultural systems (Karthika & Surendar, 2025).

Table 2. Impact of management practices on crop yield and soil organic carbon in temperate soils

Management Scenario	Average Crop Yield (Mg ha^{-1})	Annual SOC Change (Mg C ha^{-1} yr^{-1})	Notes
Baseline (Conventional)	7.8	0	Standard practice baseline
Improved Nitrogen Management	8.1	0	Optimized N application, increased yield
Conservation Tillage	7.5	+0.45	Carbon sequestration benefit, slight yield dip

As shown by the analytical evaluation presented in Table 2, different management strategies affect the output of crops and the variation in the soil organic carbon (SOC) within a period of 10 years. The baseline of conventional practice in terms of average yield of the crop was 7.8 Mg ha1 and had no significant change in SOC. There was higher nitrogen control and crop yield grew to 8.1 Mg ha1, which showed that the optimal fertilization is productive and does not affect SOC adversely. Furthermore, conservation tillage enhanced SOC by 0.45 Mg C ha1 yr1 showing a better carbon sequestration; but yield was a little less at 7.5 Mg ha1. Such is an example of a trade-off in which conservation practices enhance the health of the soil at the expense of temporary crop production.

The DNDC model did a good job capturing the interactions of soil, climate, management land sob carbon and nitrogen cycles in temperate soils. improving nitrogen management in combination with some conservation tillage practices had potential for reduced greenhouse gas emissions and nutrient leeching is more sustainable agriculture and climate change mitigation. These findings strengthen the model's credibility as a decision-support system for policy and governance in the environment and land use for temperate agroecosystems.

Conclusion

This work was successful in employing the DNDC (Denitrification Decomposition) model to model the carbon and nitrogen dynamic in different soils, climates, and management of soils in temperate agroecosystems. The model simulated various processes such as the soils, cropping, emission of greenhouse gasses, loss of nitropen, and model validation against field data verified the results of the models. The original situation revealed the modern management systems emission inefficiencies on N2O and nitrate leaching that were magnanimously and paradigmatically unfavorable. As far as the limited nitrogen management situation is concerned, a significant attenuation potential was observed, emissions and nutrient losses in the situation were suppressed and crop yields were maintained or increased. The conservation tillage practices were also successful in enhancing the stocks of soil organic carbon and CO2 emission although there were trade-offs of N2O fluxes as a result of certain soil conditions at the sites. To defend the agricultural practices, the process-based models DNDC that are included in the highlighted are useful in estimating its environmental impact and developing climate-sensitive solutions. Certainly, this also supports the information given in the model on sustainable land use to alleviate the productivity pressures in the temperate region setting in a climate-stressed environment. Such an examination asserts very plausible results, nonetheless, there are a number of voids that should be sealed so as to augment the usefulness and accuracy in DNDC simulations. The use of DNDC model could also be complemented by the introduction of new methods of crop production like intercropping, agro forestry that would make land use systems more versatile. Moreover, incorporation of the high-resolution remote sensing and geospatial soil databases may enable the regional and even national evaluations, extending the boundaries of simulations. Better modeling of microbial processes would improve model outputs especially when microbial processes happen at their extreme conditions such as droughts and heavy rainfall. Furthermore, field experiments over extended durations would also give data to be used in the calibration and validation of the model in a seamless manner with climatic conditions, which will be useful in validating sustainability-related results across the changing climatic conditions. Socio-economic parameters might also be included to help the design of mitigation strategies that may be more practical in their implementation. Such integration of DNDC into other models, e.g., hydrological or economical models would provide decision-support system of climate change policy-makers that is comprehensive and deals with reduction of emissions and with planting of resilient, low greenhouse gas emitting agricultural landscapes in the temperate areas.

References

Almeida-Neto, M., & Ulrich, W. (2011). A straightforward computational approach for measuring nestedness using quantitative matrices. *Environmental Modelling & Software*, *26*(2), 173-178. https://doi.org/10.1016/j.envsoft.2010.08.003

Culpa, E. M., Mendoza, J. I., Ramirez, J. G., Yap, A. L., Fabian, E., & Astillo, P. V. (2021). A Cloud-Linked Ambient Air Quality Monitoring Apparatus for Gaseous Pollutants in Urban Areas. *Journal of Internet Services and Information Security, 11*(1), 64-79. https://doi.org/10.22667/JISIS.2021.02.28.064

Del Prado, A., Merino, P., Estavillo, J. M., Pinto, M., & González-Murua, C. (2006). N2O and NO emissions from different N sources and under a range of soil water contents. *Nutrient cycling in agroecosystems*, *74*(3), 229-243. https://doi.org/10.1007/s10705-006-9001-6

Gandhi, N., Prakruthi, B., & Vijaya, C. (2024). Effect of Industrial Emissions on Haematological and Biochemical Parameters of Channa striata Fresh Water Fish. *International Journal of Aquatic Research and Environmental Studies*, *4*(1), 115-119. http://doi.org/10.70102/IJARES/V4I1/10

Giltrap, D. L., Li, C., & Saggar, S. (2010). DNDC: A process-based model of greenhouse gas fluxes from agricultural soils. *Agriculture, ecosystems & environment*, *136*(3-4), 292-300. https://doi.org/10.1016/j.agee.2009.06.014

Gladkov, E. A., & Gladkova, O. V. (2021). Plants and maximum permissible concentrations of heavy metals in soil. *Archives for Technical Sciences*, *2*(25), 77-82. http://doi.org/10.7251/afts.2021.1325.077G

Harrison, R. M., Brunekreef, B., Keuken, M., Van Der Gon, H. D., & Querol, X. (2014). New Directions: Cleaning the air: Will the European Commission's clean air policy package of December 2013 deliver?. *Atmospheric Environment*, *91*, 172-174. https://doi.org/10.1016/j.atmosenv.2014.04.027

Kanagala, S., Al Khalaifin, M. H. S. S., Al-Harthi, A. A. R. S., & Al-ahdhami, S. S. A. (2023). Greenhouse Farm Monitoring is Automated with Smart Controls. *International Academic Journal of Science and Engineering*, *10*(1), 27-32. https://doi.org/10.9756/IAJSE/V10I1/IAJSE1005

Karthika, J., & Surendar, A. (2025). AI-Augmented DNDC Modelling Framework for Carbon and Nitrogen Flux Prediction in Climate-Smart Agricultural Systems. *National Journal of Smart Agriculture and Rural Innovation, 3*(2), 11-19.

Li, C. (2007). Quantifying greenhouse gas emissions from soils: Scientific basis and modeling approach. *Soil Science and Plant Nutrition*, *53*(4), 344-352. https://doi.org/10.1111/j.1747-0765.2007.00133.x

Li, C., Frolking, S., & Frolking, T. A. (1992). A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. *Journal of Geophysical Research: Atmospheres*, *97*(D9), 9759-9776. https://doi.org/10.1029/92JD00509

Liu, X., Niu, D., Bao, C., Suk, S., & Shishime, T. (2012). A survey study of energy saving activities of industrial companies in Taicang, China. *Journal of Cleaner Production*, *26*, 79-89. https://doi.org/10.1016/j.jclepro.2011.12.030

Mohan, G., Gokul, V., Praveenkumar, V., & Menaka, S. R. (2023). Plant Disease Detection and Classification using Machine Learning Algorithm. *International Journal of Advances in Engineering and Emerging Technology*, *14*(1), 137-141.

Nakamura, Y., & Lindholm, M. (2025). Impact of Corn Production on Agriculture and Ecological Uses of Olive Mill Sewage using Ultrafiltration and Microfiltration. *Engineering Perspectives in Filtration and Separation*, 13-17.

Narayanan, L., & Rajan, A. (2024). Artificial Intelligence for Sustainable Agriculture: Balancing Efficiency and Equity. *International Journal of SDG's Prospects and Breakthroughs*, 4-6.

Prabhakar, C. P. (2024). Model-Based Assessment of Soil Carbon–Nitrogen Interactions and Their Impact on Sustainable Food Productivity Using the DNDC Framework. *National Journal of Food Security and Nutritional Innovation*, *2*(2), 10-18.

Rajalakshmi, A. R., Jayakani, S., Shanmugam, H., & Ramakrishnan, P. R. (2024). Green Products and Electronic Word of Mouth: A Study Special Reference with Significance of Environmental Concern, Knowledge and Consciousness. *Indian Journal of Information Sources and Services*, *14*(4), 79-85. https://doi.org/10.51983/ijiss-2024.14.4.13

Robertson, G. P., & Vitousek, P. M. (2009). Nitrogen in agriculture: balancing the cost of an essential resource. *Annual review of environment and resources*, *34*, 97-125. https://doi.org/10.1146/annurev.environ.032108.105046

Sainju, U. M., Jabro, J. D., & Stevens, W. B. (2008). Soil carbon dioxide emission and carbon content as affected by irrigation, tillage, cropping system, and nitrogen fertilization. *Journal of environmental quality*, *37*(1), 98-106. https://doi.org/10.2134/jeq2006.0392

Sethi, K., & Jain, R. (2024). Smart grid technologies and renewable integration: Contributions to the Periodic Series in electrical and environmental innovation. In *Smart grid integration* (pp. 26–32). *Periodic Series in Multidisciplinary Studies*.

Shrirao, N. M., & Mishra, N. (2024). Integration of DNDC Soil Flux Modelling with Forage Productivity Assessment for Sustainable Livestock Feed Systems. *National Journal of Animal Health and Sustainable Livestock*, *2*(2), 11-19. https://doi.org/10.17051/NJAHSL/02.02.02

Smith, J. O., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R. J., ... & Ewert, F. (2005). Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. *Global Change Biology*, *11*(12), 2141-2152. https://doi.org/10.1111/j.1365-2486.2005.001075.x

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., ... & Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical transactions of the royal Society B: Biological Sciences*, *363*(1492), 789-813. https://doi.org/10.1098/rstb.2007.2184

Sorrenti, G., Masiello, C. A., Dugan, B., & Toselli, M. (2016). Biochar physico-chemical properties as affected by environmental exposure. *Science of the total Environment*, *563*, 237-246. https://doi.org/10.1016/j.scitotenv.2016.03.245

Sreenivasulu, G. (2024). A Hybrid Optical-Acoustic Modem Based on Mimo Ofdm for Reliable Data Transmission in Green Underwater Wireless Communication. *Journal of VLSI circuits and systems*, *6*(1), 36-42. https://doi.org/10.31838/jvcs/06.01.06

Srimuang, C., & Doungmala, P. (2023). Autonomous flying drones: Agricultural supporting equipment. *International Journal of communication and computer Technologies*, *11*, 7-12.

Vaduganathan, D., & Geetha, K. (2024). Modelling Carbon and Nitrogen Dynamics in Integrated Aquaculture–Agriculture Systems Using the DNDC Framework. *National Journal of Smart Fisheries and Aquaculture Innovation, 2*(2), 9-15.

Veerasamy, K., & Fredrik, E. T. (2023). Intelligence System towards Identify Weeds in Crops and Vegetables Plantation Using Image Processing and Deep Learning Techniques. *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications*, *14*(4), 45-59. https://doi.org/10.58346/JOWUA.2023.I4.004

Vij, P., & Prashant, P. M. (2024). Analyzing Soil Pollution by Image Processing and Machine Learning at Contaminated Agricultural Field. *Natural and Engineering Sciences*, *9*(2), 335-346. https://doi.org/10.28978/nesciences.1575484

Wiśniewski, K. P., Zielińska, K., & Malinowski, W. (2025). Energy efficient algorithms for real-time data processing in reconfigurable computing environments. *SCCTS Transactions on Reconfigurable Computing*, *2*(3), 1-7.

Xiang, P., Afsari, F., & Dong, L. (2017). Cement industrial impacts on greenhouse emission and evaluating the reduction strategies. *International Academic Journal of Innovative Research, 4*(2), 80-8.

Yousefi, B., Jafari, A., & Naghipour, A. A. (2025). Habitat suitability modelling of wild goat using Maximum entropy (MaxEnt) model in Hormood protected area (Fars province, Iran). *Journal of Animal Environment*, *17*(1), 1-8.

Zhang, W. F., Dou, Z. X., He, P., Ju, X. T., Powlson, D., Chadwick, D., ... & Zhang, F. S. (2013). New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. *Proceedings of the National Academy of Sciences*, *110*(21), 8375-8380. https://doi.org/10.1073/pnas.1210447110

Zhang, Y., Li, C., Zhou, X., & Moore III, B. (2002). A simulation model linking crop growth and soil biogeochemistry for sustainable agriculture. *Ecological modelling*, *151*(1), 75-108. https://doi.org/10.1016/S0304-3800(01)00527-0