# A review and outlook on the development and application of the DNDC model

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**Key Points:**

- DNDC effectively models soil processes and gas emissions, predicts environmental and climate impacts, and adapts to diverse ecosystems.
- DNDC's limitations include lower accuracy in wetlands and simplified biogeochemical assumptions. Improvements in these areas are needed.
- DNDC's source code is private, hindering its verification and improvement. Its public release could enhance scientific progress.

## Abstract

Denitrification-Decomposition (DNDC) model, a mathematical construct that simulates biogeochemical processes including carbon and nitrogen dynamics, plant growth, and microbial activity across various ecosystems. The discourse includes an examination of the model's developmental trajectory, with attention given to adaptations created for diverse ecosystems, regions, specific crops, and modular configurations. We additionally delve into the validation processes of the DNDC model and its broader applications across different fields. Despite the model's extensive usage in previous studies, there has been a lack of critical, comprehensive evaluation of its merits and demerits. This paper aim to address this gap, providing a thorough critique and review of the DNDC model. In our discussion, we present a balanced overview of the DNDC model's current strengths and weaknesses, and offer insights into its potential future developments. The ultimate goal of this paper is twofold. Firstly, we aim to provide guidance to researchers and practitioners who are either currently employing or considering the use of the DNDC model. Secondly, our critique and analysis is intended to be a constructive contribution towards the model's future refinement and development.

## Plain Language Summary

This paper presents a critical evaluation of the Denitrification-Decomposition (DNDC) model, which accurately simulates biogeochemical processes in ecosystems. It thoroughly explores the model's development, adaptations, validation processes, and diverse applications. The primary objectives are to address the lack of comprehensive evaluation, offer a balanced overview of its strengths and weaknesses, provide guidance to researchers and practitioners, and contribute constructively to the model's refinement and future development.

# 1 Introduction

Nitrous oxide ($N_2O$) is one of the powerful greenhouse gases (GHG) (Gilhespy et al., 2014), and agriculture is the largest anthropogenic non-$CO_2$ emissions source, accounting for approximately 40% of total methane ($CH_4$) emissions and 60% of $N_2O$ emissions. This accounts for 10-12% of the total anthropogenic GHG emissions (including $CO_2$, which accounts for up to 20-35%) , and this proportion is increasing annually (Frank et al., 2019; US-EPA, 2006). Methane ($CH_4$) is the second largest contributor to global warming, and understanding how to mitigate $CH_4$ emissions is critical (Shaukat et al., 2022). As global climate change intensifies, developing a biogeochemical model to simulate carbon and nitrogen emissions at both regional and global scales has become a hot research topic (Del Grosso et al., 2006; Giltrap et al., 2010). As early as 1998, there were more than 30 international models of biogeochemical processes (Cao & Woodward, 1998), and now there are hundreds more, often based on mathematical formulas and computer codes, which are used to simulate and predict various aspects of biogeochemical cycling in ecosystems. These models vary in complexity and accuracy, with some being very simple, containing only a few equations, while others are very complex, involving thousands of equations and parameters. The DNDC model has become one of the most widely used biogeochemical cycling models internationally for simulating carbon and nitrogen biogeochemical cycling processes at the site and regional scales in different ecosystems (C. S. Li, 2000). The reason is simple. On one hand, DNDC model combines redox potential reaction, the Gibbs equation, and other biogeochemical theories to observe, analyze, and predict the carbon cycle of terrestrial ecosystems at a point and regional scale. It passes information with a time step of hours or days, simulating processes such as carbon and nitrogen emissions, crop yield, soil carbon sequestration, and nitrate leaching. Thus, it provides a basis for appropriate ecosystem management for local meteorology and soil quality and is widely used in research on estimating greenhouse gas emissions, dynamic changes in soil organic carbon, and soil nitrogen loss. On the other hand, the model has a simple software interface, easy-to-understand parameter settings, customizable parameters, and a wide range of applications, providing users with considerable flexibility. Therefore, it can be well applied to carbon and nitrogen cycle simulation research, addressing biogeochemical issues such as climate change (Hastings et al., 2010; Syp et al., 2012; Gilhespy et al., 2014).

Since the mid-20th century, with the development of technological means and the support of fundamental scientific theories and computational technology, domestic and foreign researchers have established various models to simulate the carbon and nitrogen cycles of ecological systems at different spatial and temporal scales. Representative biogeochemical process models currently include the CENTURY, RothC, APSIM, and DNDC models, among others (C. Li et al., 1992). For example, W. N. Smith et al. (2000) used the CENTURY model to analyze soil organic carbon changes in Canadian farmland from 1970 to 2010, finding that no-tillage practices can transform farmland soil from a carbon source to a carbon sink. Afzali et al. (2019) used the RothC model to study the impact of agricultural management changes on global farmland soil organic carbon, discovering that returning straw to fields increased soil organic carbon density by 0.22-0.69 mg·hm-2 from 1961 to 2014. Beah et al. (2020) used the RothC and APSIM models to investigate grassland's effect on soil organic carbon storage in the arid region of southern Iran and the impact of nitrogen fertilizer application on corn yield, respectively. There are also other models that can be used to simulate other biogeochemical processes such as T. Luo et al. (2022) used the EPIC model to estimate soil erosion coefficients and assess predicted soil erodibility factors in karst watersheds. Y. Wang et al. (2023) employed InVEST and CASA models to analyze the spatial distribution patterns of nine ecosystem services in the Qilian Mountains from 2000 to 2018.

## 2 Development of the DNDC Model

### 2.1 The scientific structure of the DNDC model

C. Li (2016) elaborated the detailed sub-modules and processing mechanisms of the model, as shown in **Fig. 1**, and discussed the scientific basis and computational processes that support the model in the book "Biogeochemistry: Science Fundamentals and Modeling Methods."

The DNDC model has the capacity to model complex processes in agricultural ecosystems, estimate dynamic changes in soil carbon and nitrogen, and predict crop yield in various ecosystems. It can be combined with GIS technology for large-scale regional simulations, making it valuable for long-term fixed-point observation data integration and predictions. Its outputs include emissions of gases like carbon dioxide and methane, crop yield, soil organic carbon content, and nitrate leaching (Li et al., 1997; Li, 2000)

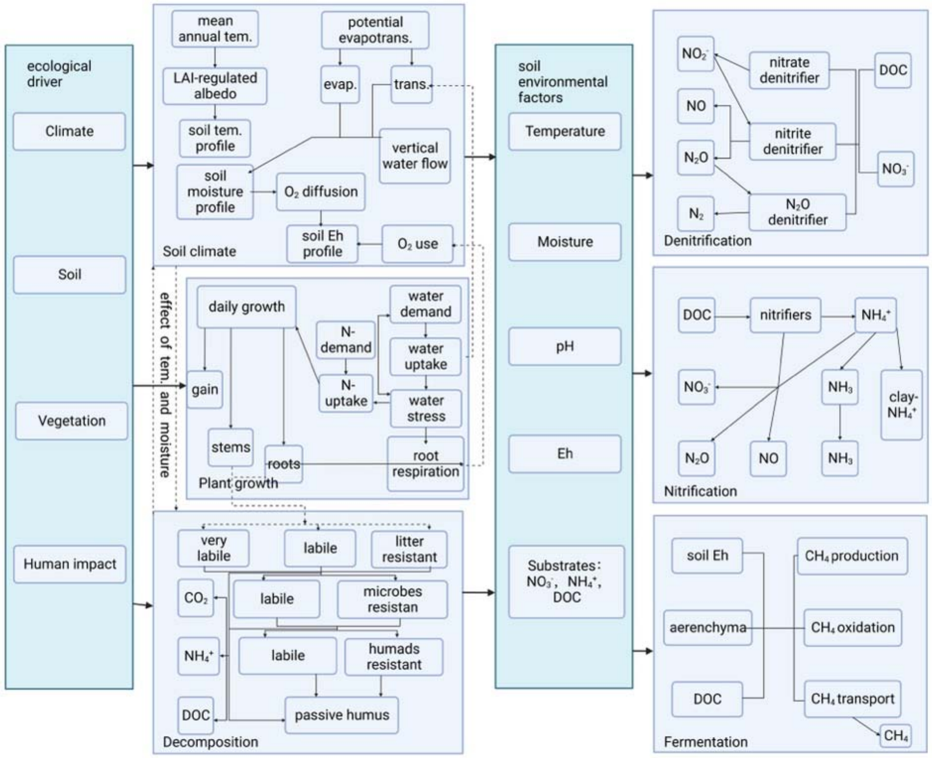


**Fig. 1** The scientific structure of the DNDC model

The first component of the DNDC model simulates the environmental driving forces within an ecosystem using various driving factors of the ecosystem's macrostructure, which form the biogeochemical field of the target ecosystem. The second component simulates the impact of the environment on microbial activity and calculates the emission of major greenhouse gas in the plant-soil system. These environmental forces in the biogeochemical field in the field of biogeochemistry follow the principles of chemical thermodynamics and reaction kinetics, determining the direction and rate of all biogeochemical and biochemical reactions in the ecosystem (C. Li, 2016).

2.2 Model modification and development

The DNDC (Denitrification-Decomposition) model, first developed by Changsheng Li at the University of New Hampshire, is a biogeochemical model used to simulate complex ecosystem processes such as carbon and nitrogen cycling. It comprises six sub-models that deal with soil climate, plant growth, organic matter decomposition, nitrification, denitrification, and fermentation. These sub-models exchange parameters to simulate the migration and transformation of carbon and nitrogen within ecosystems (Li, 2000; Giltrap et al., 2010).

Long-term monitoring of soil organic carbon (SOC) is ideal but is often limited by the scale of the experiment, monitoring sites, and duration, making it difficult to accurately determine small-scale spatiotemporal changes (Y. Zhao et al., 2018). Furthermore, estimation of agricultural $NH_3$ and $N_2O$ emissions traditionally relied on fixed emission factors without considering atmospheric, soil, crop, and management factors, leading to uncertainty (Yue et al., 2019; Zhan et al., 2021). Hence, process-based models like DNDC that integrate environmental factors and management practices are preferred for predicting large-scale changes in SOC dynamics and $N_2O$ and $NH_3$ emissions (H. Li et al., 2017).

The DNDC model excels in simulating the entire soil carbon and nitrogen cycle, incorporating driving factors such as air temperature, nitrogen fertilizer, precipitation, soil organic carbon, and agricultural management practices (Zhang et al., 2009; Xu et al., 2019; Zhao et al., 2020). It predicts soil conditions and gas emissions, including $CO_2$, $CH_4$, $NH_3$, NO, $N_2O$, and $N_2$ from farmland (Li et al., 2000; Fumoto et al., 2008; Dou et al., 2014; Zhao et al., 2020). With broad applications and continuous enhancements from global research, the DNDC model's functions have expanded to include tracking greenhouse gas emissions, detecting plant growth, microbial activity, soil carbon sequestration, and modeling various ecosystems such as forests, wetlands, and grasslands (Fillery et al., 1986; Rafique et al., 2011; Chen et al., 2013). The development and some modifications of the DNDC model are shown in Table 1.

**Table 1** The development and modifications of the DNDC model

| Publications | Model Version | Functions |
|---|---|---|
| C. Li et al. (1992) | DNDC v. 1.0-7.0 | There are three basic sub-models in the DNDC model: the soil climate/water heat flux sub-model, the organic carbon decomposition process sub-model, and the denitrification sub-model (which includes only one equation for nitrification when there is no crop growth) . |
| C. Li et al. (1994) | DNDC v. 7.1 | The initial version was improved by adding a plant growth process submodel and a land management use submodel. |
| C. Li et al. (2000) | PnET-N-DNDC | Integrated the models of photosynthesis, evapotranspiration, DNDC, and nitrification, replacing crop growth with forest growth, which can predict the emissions of $N_2O$ and NO in forest soils. Introduced the concept of "anaerobic balloon" and considered the influence of freezing and thawing on soil moisture. |
| Li, (2000) and Li et al. (2000) | DNDC v. 8.0 | A new two-component model framework was developed in the PnET-N-DNDC model, incorporating a submodel that simulates fermentation processes using soil redox potential. The model integrates the anaerobic chamber concept along with freeze-thaw effects. |
| Y. Zhang, Li, Zhou, et al. (2002) | Crop-DNDC | Simulating crop growth through physiological processes under water and nitrogen stress, a new phenology crop submodel incorporating the initial version submodels (decomposition, nitrification, and denitrification) was introduced. |
| Y. Zhang, Li, Zhou, et al. (2002) | DNDC v. 8.2 | The new phenology crop submodel was introduced into the DNDC model as a replacement for the empirical crop growth submodel added in 1994. The new phenology crop physiological and ecological model requires more and finer plant growth parameters, while the simulated results are more accurate. |
| Y. Zhang, Li, Trettin, et al. (2002) | Wetland-DNDC | To predict $CO_2$ and $CH_4$ emissions in wetland ecosystems, we integrated the PnET-N-DNDC and FLATWODS models that are suitable for such ecosystems. We introduced dynamic changes in water levels and modified soil |

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| | | properties and climatic conditions. The resulting model comprises four submodels: hydrological conditions, soil temperature, plant growth, and soil carbon dynamics. |
| Brown et al. (2002) | UK-DNDC | Adapting the DNDC model for simulating UK ecosystems. |
| C. Li, Cui, et al. (2004) | DNDC v. 8.5 | Modified the concept of "anaerobic gas vesicle" by incorporating the Nernst equation and combining it with the Michaelis-Menten equation. |
| Saggar et al. (2004) | NZ-DNDC | Modified the model of annual crops to that of perennial grass growth, quantified the nitrogen input from herbivore excreta, replaced the Thorthwaite equation with the Priestley-Taylor equation to calculate potential soil evapotranspiration, and changed the order of soil water infiltration and drainage to simulate the $N_2O$ emission patterns from New Zealand grassland. |
| C. Li, Mosier, et al. (2004) | DNDC-Rice | Modified the DNDC model to make it applicable to rice paddy ecosystems. Further improvements were made by Rafique et al. (2011) in Indian rice paddies. Fumoto et al. (2008) enhanced and integrated the MACROS implementation. |
| C. Li et al. (2005) | Forest-DNDC | Integrated the PnET and DNDC models for both dryland and wetland forest ecosystems. |
| Kiese et al. (2005) | Forest-DNDC-Tropica | Modified the PnET-N-DNDC model to make it applicable to tropical rainforest ecosystems. |
| Neufeldt et al. (2006) | EFEM-DNDC | Coupling EFEM and DNDC v8.0 to simulate greenhouse gas emissions from typical livestock and production systems in Baden-Württemberg, Germany, using a GIS-coupled economic-ecological system model. |
| C. Li et al. (2006) | DNDC v. 9.0 | Introducing free ammonium kinetics and improving the leaching of nitrification and nitrate to optimize the accuracy of the model simulation. |
| Beheydt (2006) | BE-DNDC | Combining DNDC v8.3P with regional data from Belgium to calculate the regional framework for $N_2O$ emissions from intensive agricultural land. |
| Fumoto et al. (2008) | DNDC-Rice | Making the DNDC-Rice model capable of simulating rice paddies with different flooding regimes. |
| Leip et al. (2008) | DNDC-Europe | Integrating CAPRI into DNDC to assess the impact of agricultural |

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| | | environmental policies on greenhouse gas emissions. |
| Grote et al. (2009) and Grote et al. (2011) | Mobile-DNDC | Linking MoiBiLE to one-dimensional ecosystem models such as DNDC to obtain the most suitable model combination for specific research tasks. MoBiLE-DNDC was adapted by Wolf et al. (2012). |
| W. N. Smith et al. (2010) | DNDC v. 9.3 | Improve the estimation of soil evaporation in the DNDC model. |
| Kröbel et al. (2011) | DNDC-CSW | Incorporate the CSW (Canadian spring wheat) empirical sub-model into the DNDC model to more accurately estimate the growth and nitrogen uptake of spring wheat in Canadian agricultural ecosystems. |
| Y. Zhang et al. (2012) | NEST-DNDC | Develop an integrated approach to quantify $CH_4$ emissions under permafrost conditions and combine DNDC with NEST. |
| C. Li et al. (2012) | Manure-DNDC | Predict GHG and $NH_3$ emissions from manure generated by farms, and modify DNDC to represent the manure lifecycle on farms. |
| C. Li et al. (2012) | DNDC v. 9.4 | Introduce the soil $NH_3$ algorithm developed by Manure-DNDC. |
| Haas et al. (2013) | Landscape-DNDC | Use DNDC and Forest-DNDC as a universal soil biogeochemical module to simulate multiple ecosystems. |
| Z. Zhao et al. (2014) | DNDC v. 9.5 | The DNDC v9.5 version is the current version, which includes optimized modules for crop growth simulation, hydrology, greenhouse gas emission-related parameters, etc., to meet the needs of greenhouse gas mitigation research. |
| Katayanagi et al. (2017) | DNDC v. 9.5 | Revised the emission factors (EFs) to consider the effects of $CH_4$ emissions. |
| Dutta et al. (2018) | DNDC v. 9.5 | The model mechanism was calibrated under two strongly contrasting soil textures (sandy and clay soils) . The calculation of soil temperature driven by soil thermal conductivity and heat capacity was improved, and the surface soil temperature mechanism of DNDC was improved to improve greenhouse gas prediction. |
| Amponsah et al. (2019) | DNDC-OP | Combine PAH degradation rates with dynamic soil, vegetation, and climate factors (such as soil moisture and temperature) to simulate the degradation dynamics of PAHs in soil at abandoned oil and gas well sites. |
| Dubache et al. (2019) | DNDC v. 9.5 | The regulation of soil moisture on urea hydrolysis was increased, and the |

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| | | temperature regulation parameterization of this process was calibrated. The volatilization coefficient of $NH_3$ released from soil water to the atmosphere above bare soil or tree canopy was redefined. The regulation of soil texture (expressed as clay fraction) and the regulation of wet and/or dry canopy were redefined, as well as the parameterization of wind speed, soil temperature, and moisture regulation. |
| He et al. (2019) | DNDC v. 9.5 | The DNDC model was modified to improve alfalfa growth simulation. |
| S. Li et al. (2019) | DNDC v. 9.5 | The calculation of soil moisture was modified, and parameterization for temperature regulation was designed when defining the rate constant for ammonium bicarbonate (ABC) decomposition and $NH_3$ release to the atmosphere. The regulation of texture on $NH_3$ volatilization from soil was re-parameterized. An adaptation coefficient was added for an unknown regulatory factor that affects the volatilization of dissolved $NH_3$. In addition, pedo-transfer functions (PTFs) were introduced into the model to estimate soil hydraulic parameters using physical and chemical properties as model inputs. |
| Cui & Wang (2019) | DNDC v. 9.5 | The original DNDC model was modified to better represent rainfall-snowfall partitioning, snow cover, and soil freeze-thaw cycles, thereby improving soil temperature simulation, particularly predicting soil temperature and greenhouse gas emissions in cold regions with snow cover during winter. |
| W. Smith et al. (2020) | DNDC v. 9.5 | The soil hydrological framework of DNDC was strengthened, including a new mechanized tile drainage submodel, improved water flux, root growth dynamics, and deeper heterogeneous soil profiles. |

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### 2.3 The core processes of the DNDC model are as follows.

The DNDC model is composed of an input interface, a biogeochemical field, and central processes. It offers users the flexibility to provide ecological driving factors, such as meteorological data, soil parameters, crop parameters, and management strategies, for the ecosystem under consideration (Yin et al., 2020). Should there be any inconsistencies between the default parameters and the actual conditions, users are granted the ability to implement tailored adjustments within the documentation. The parameters corresponding to the target ecosystem will be utilized to form the biogeochemical field and transform the input driving factors into the propelling forces for the various sub-models housed within the model. Prior to executing calculations and simulations for carbon, nitrogen, and water in the ecosystem, the core processes establish the biogeochemical reactions.

#### 2.3.1 Climatic Conditions of Soil

The DNDC model serves as a tool for simulating gas emanations from the soil, where the generation of $CO_2$, $CH_4$, and $N_2O$ primarily arises from microbial actions. These actions, in turn, are largely governed by the prevailing conditions within the soil environment (Yin et al., 2020). The precise replication of soil climate factors, encompassing soil temperature, hydration levels, pH, redox potential (Eh), along with corresponding substrate concentrations, is of paramount importance for monitoring greenhouse gas emissions. The model meticulously computes the soil temperature for each layer, utilizing parameters like the rate of heat transfer, the specific heat capacity, and the thermal conductivity of the soil. It also maintains an equilibrium between water input and output to ascertain the moisture content within each layer. These measures ensure the model's adaptability for frigid and snow-laden environments. Cui & Wang (2019) modified the rainfall and snowfall submodules and embedded the agricultural snow model into the DNDC model to more effectively simulate the impact of rain and snow on soil temperature and moisture. Katayanagi et al. (2012) improved the modeling of soil infiltration and evapotranspiration by estimating soil moisture content in each layer every hour using the DNDC-Rice model. The water permeability (1 mm/day for a 50 cm deep soil layer) was determined by comparing soil moisture content with irrigation parameters and irrigation time, thereby establishing a dynamic water model for continuous irrigation and wet-dry alternation. Pathak et al. (2005) increased the leakage rate of certain reactive substrates in the soil, such as dissolved organic carbon (DOC) and nitrate, in the model. The optimization results of the model greatly reduced $CH_4$ emissions at high leakage points, but had no effect on $CH_4$ emissions at low or moderate leakage points.

#### 2.3.2 Progression of Plant Development

Indeed, the progression of plant growth wields a considerable impact on the fluctuations of water, carbon, and nitrogen within the soil, commanding many of the biogeochemical processes that take place therein. This is a crucial facet in guaranteeing that the DNDC model precisely replicates the oscillations of carbon and nitrogen within the interconnected cycle of soil, plant, and atmosphere (Yin et al., 2020). The architects of the model conceived a crop-specific sub-module, incorporating pertinent crop growth models to faithfully replicate the progression of crop development. To illustrate, straightforward empirical formulas, photosynthesis and evapotranspiration processes, the agricultural emissions financial model, the northern ecosystem's soil temperature dynamics, and the annual crop simulator module of the general crop model were all skillfully integrated (Zhang et al., 2002b; Li et al., 2004b).

### 2.3.3 Dynamics of Soil Carbon

Within the DNDC model, the ecosystem's soil carbon is compartmentalized into four primary reservoirs: plant debris, microorganisms, active humus, and passive humus. Each reservoir is further subdivided into two or three sub-reservoirs, with each sub-reservoir exhibiting a distinct rate of decomposition. The rate at which organic carbon decomposes within each sub-reservoir is contingent upon a multitude of factors. These include the size of the reservoir, the soil's temperature and hydration levels, the extent of clay content within the soil, and the amount of nitrogen present in the soil, as shown in **Fig 2**.

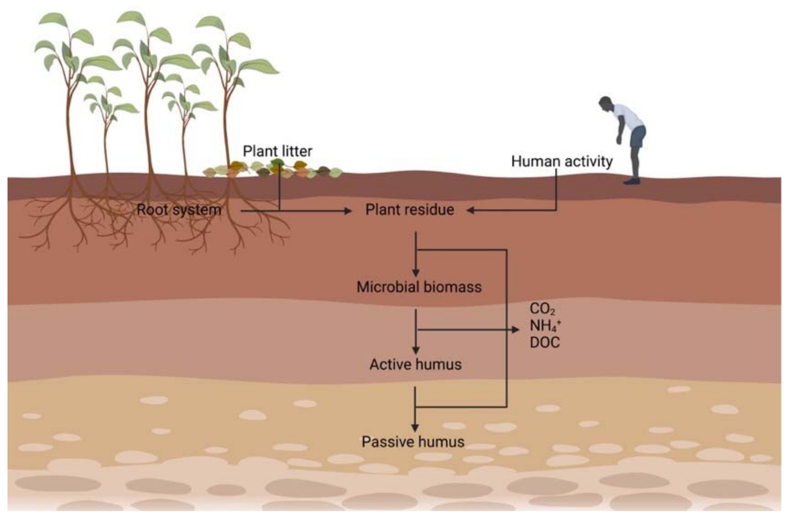


**Fig 2** Soil carbon dynamics

Plants and microorganisms harness the power of Soil Organic Carbon (SOC), playing a fundamental role in the cyclical processes of carbon and nitrogen. The agglomeration of crop detritus, animal waste, biochar, and microbial leftovers in rice soil serves as a major contributor to the soil organic carbon reservoir. External carbon contributions are apportioned among various sub-reservoirs of SOC, taking into account their inherent physical and chemical attributes, with pre-established rates dictating the pace of decomposition. The disintegration process is subject to an array of influences which include the nature of the organic substance and the granular constitution of the soil (C. Li, 2016).

### 2.3.4 Emissions of Greenhouse Gases

Various redox reactions taking place in the soil, such as decomposition, nitrification/denitrification, and methane production, contribute to the generation and consumption of soil gases like CO2, CH4, and N2O. The redox potential or Eh sets the stage for whether these reactions can occur. The model creates what is termed an "anaerobic balloon", employing the Michaelis-Menten equation. This quantifies the kinetic influence of substrate concentration on the reaction rate, thereby facilitating the thermodynamic and kinetic computations of greenhouse gas-triggered redox reactions. Based on the modelled content of oxygen or other oxidizing agents in the soil, DNDC employs the Nernst equation to establish the total redox potential (Eh) of the soil. It then predicts the potential redox reactions based on the Eh, segregating the soil into relatively aerobic and anaerobic sections. Nitrification transpires in the aerobic sections, while denitrification ensues in the anaerobic sections. The rate of either nitrification or denitrification is computed using the Michaelis-Menten equation, which depicts microbial growth as a function of the concentration of two nutrients.

## 3 Validation for DNDC Model

Validation methods available for DNDC models include parameterization, calibration, and validation against field data. These methods require adjusting model parameters to match field data and assessing the model's ability to accurately predict greenhouse gas emissions and soil dynamics in diverse agricultural systems. Inter-model comparisons can also be utilized to evaluate the accuracy of the DNDC model compared to other models. Numerous studies have demonstrated the effectiveness of the DNDC model and its validation methods in simulating methane and nitrous oxide emissions, soil organic carbon dynamics, and crop performance in various agricultural systems.

## 4 Application of DNDC Model

The DNDC model addresses two main issues: first, the impact of extreme weather events and potential climate change on greenhouse gas emissions; second, the assessment of the emission reduction potential of various mitigation measures. The DNDC model can simulate different ecosystems at the point and regional level, respectively.

### 4.1 Site

The DNDC model simulates ecosystems at the point level by using observed data from different sites as inputs. The applications of the DNDC model in point-scale ecosystem research are presented in **Table 2**.

### 4.2 Region

The DNDC model can be used to simulate greenhouse gas emissions at the regional scale, as shown in **Table 3**. The use of the DNDC model at the regional scale is similar to other GIS data-driven models, where soil and climate parameters are identical by default, and soil and climate parameters of different "grid cells" are stored in a dedicated GIS database. Different agricultural ecosystem types can be configured with different management measures, but the agricultural ecological management measures for each grid cell are unique.

**Table 2** Application of the DNDC model to point locations

| Publications | Ecosystem | Simulation parameter | Region |
|---|---|---|---|
| Du et al. (2011) | Alpine meadow | $N_2O$ | China |
| Kang et al. (2020) | Alpine wetland | SOC | China |
| J. Zhang et al. (2017) | Cropland | Yield | China |
| Jarecki et al. (2018) | Cropland | Yield | Canada |
| S. Li et al. 2019) | Cropland | $NH_3$ | China |
| Dubache et al. (2019) | Cropland | $NH_3$ | UK |
| Abdalla et al. (2020) | Cropland | $N_2O$, Yield | China |
| Jiang et al. (2021) | Cropland | $N_2O$ | Canada |
| Hussain Shah et al. (2021) | Cropland | Salinity | Canada |
| L. Wang et al. (2022) | Cropland | $N_2O$ | China |
| C. Wang et al. (2022) | Cropland | $N_2O$ | China |
| Abdalla et al. (2010) | Farm | $N_2O$ | Ireland |
| Y. Zhang et al. (2018) | Farm | Biomass | China |
| Q. Li et al. (2021) | Farm | $CO_2$, $N_2O$, $CH_4$ | China |
| Dou et al. (2014) | Field | SOC | USA |
| Deng et al. (2016) | Field | $N_2O$ | USA |
| Wu et al. (2018) | Grassland | SOC | China |
| Schroeck et al. (2019) | Grassland | Reactive N | Austrian |
| Shah et al. (2020) | Grassland | $N_2O$ | UK |
| Z. Zhao, Cao, Sha, et al. (2020) | Paddy | N | China |
| Hwang et al. (2021) | Paddy | $CO_2$, $CH_4$ | Korea |
| Shaukat et al. (2022) | Paddy | $CH_4$ | USA |

**Table 3** Application of the DNDC model to the regions

| Publications | Ecosystem | Simulation parameter | Region |
|---|---|---|---|
| C. Li et al. (1994) | Cropland | $N_2O$ | USA |
| C. Li et al. (1996) | Cropland | $N_2O$ | USA |
| C. Li et al. (2001) | Cropland | $N_2O$ | China |
| D. Giltrap et al. (2008) | Cropland | $N_2O$ | New |
| Qiu et al. (2011) | Cropland | $NO_3$ | China |
| Kesik et al. (2005) | Forest | $N_2O$, NO | Europe |
| C. Li, Cui, et al. (2004) | Paddy | $CO_2$, $N_2O$, $CH_4$ | China |
| Pathak et al. (2006) | Paddy | CO2, $N_2O$, $CH_4$ | India |
| Yu et al. (2011) | Paddy | $N_2O$, $CH_4$ | China |
| X. Xu et al. (2011) | Paddy | SOC, $N_2O$, $CH_4$ | China |
| Y. Zhang et al. (2011) | Paddy | $CH_4$ | China |
| Z. Wang et al. (2020) | Paddy | N, $CH_4$ | China |
| Z. Zhao, Cao, Deng, et al. (2020) | Paddy | $N_2O$, $CH_4$ | China |

### 4.3 Other application cases

The DNDC model is crucial in informing sustainable agricultural practices and mitigating greenhouse gas emissions from agricultural systems. It has been widely tested and applied worldwide for predicting soil organic carbon dynamics, greenhouse gas fluxes, and other parameters, providing valuable insights that can help reduce emissions and promote soil health (Oreskes, 2003; Zhang et al., 2006; Giltrap et al., 2010; Smith et al., 2012; Zhang et al., 2015, pp. 1981–2000), especially in simulating the nitrogen (N) dynamics of ecosystems (Li et al., 1992; Li, 2016). It also performs well in the snowy mountains (J. Luo et al., 2013) and grassy areas (W. Zhang et al., 2017) of the high-altitude permafrost region of the Tibetan Plateau.

Fumoto et al. (2008) revised a biogeochemistry model to simulate methane emissions from rice paddy fields under different residue management and fertilizer regimes. The revised model accurately simulated methane emissions and showed that residue management and fertilizer application significantly impacted emissions. The study found that using the DNDC model to simulate soil organic carbon dynamics in rice fields in China significantly improved the accuracy of the simulations compared to other models (Zhang et al., 2016). Liu et al. (2020) utilized the DNDC model to simulate the ammonia volatilization process. Their findings showed that ammonia volatilization was the principal nitrogen loss pathway and also demonstrated the effectiveness of the DNDC model in accurately predicting nitrogen loss pathways in dryland agro-ecosystems. Z. Zhao, Cao, Deng, et al. (2020) used the DNDC model to simulate methane and nitrous oxide emissions from paddy fields in Shanghai, China, and evaluated the potential for mitigation strategies. The study found that the DNDC model accurately predicted the emission patterns. Z. Wang et al. (2021) estimated methane emissions from rice fields in China using the DNDC model and found that the model was effective in predicting methane emissions. Macharia et al. (2021) parameterized, calibrated, and validated the DNDC model to estimate carbon dioxide and nitrous oxide emissions as well as maize crop performance in East Africa. The study found that the DNDC model can accurately predict crop yields and greenhouse gas emissions in East African maize fields.

## 5 Evaluation of the DNDC Model

### 5.1 Advantages of the DNDC Model

DNDC has several distinct advantages over other widely used models such as CENTURY, RothC, APSIM, EPIC, InVEST, and CASA. For example, while these models are useful for simulating biogeochemical processes, they may have shortcomings in areas such as modeling soil processes, simulating nitrogen cycling, or providing detailed assessments of land management practices. In contrast, DNDC is specifically designed to model the effects of management practices on soil processes and greenhouse gas emissions, and its ability to simulate both carbon and nitrogen cycles in soil-plant-atmosphere systems makes it a valuable tool for assessing environmental impacts and predicting climate change effects. Additionally, DNDC has been extensively validated against field data, providing a high level of confidence in its predictions. As mentioned above for some of the DNDC use cases, the simulation accuracy for GHGs is high when the model input information is accurate.

The DNDC model scalability and flexibility allow for modifications to model parameters and the addition of new ecological processes. This makes the model adaptable to various ecosystems and application scenarios. Additionally, the model's versatility in various ecosystems and application fields, including farmland, grassland, forest, and wetland, as well as agriculture, forestry, and environmental protection, provides a scientific basis and reference for ecosystem management and decision-making.

### 5.2 Limitations of the DNDC model

The DNDC model is widely used for ecosystem modeling, but it has limitations in some ecosystem types. In wetland ecosystems, the prediction accuracy of the DNDC model is lower than in other ecosystems due to simplified assumptions about soil waterlogging and plant growth. Moreover, the model lacks a detailed description of biogeochemical cycling processes, which may also affect its accuracy. When using the DNDC model in different ecosystem types, its predictive accuracy and adaptability may be limited. This is because the model's response and adaptation to geographic variability are limited. Therefore, it is necessary to carefully consider these limitations when applying the DNDC model to different ecosystems and management scenarios. Future research should focus on improving the model's accuracy and adaptability, especially in wetland ecosystems, by incorporating more detailed descriptions of biogeochemical cycling processes and improving the model's response to geographic variability. The shortcomings mentioned above, whether accuracy issues or otherwise, can be adapted by modifying the source code to adapt the model to a specific ecosystem in order to obtain more precise results.

The fact that the source code of the DNDC model is not publicly available may limit the ability of researchers to verify the model's accuracy, understand its underlying processes, and make modifications or improvements. However, there may be valid reasons for not releasing the code, such as concerns about intellectual property or software security. Releasing the source code of the DNDC model can benefit scientific research by allowing for validation and improvement, promoting transparency and reproducibility, and increasing credibility and trust. Moreover, it can foster scientific progress and support informed decision-making.

## 6 Outlook

The DNDC model, despite its undeniable advantages, is not without limitations. Its precision can be significantly influenced by the quality of input data, and it may oversimplify some intricate biogeochemical processes. These factors could lead to discrepancies between the model's predictions and observed values, particularly in varied ecosystems, regions, and crops. The model's performance exhibits considerable variation across disparate geographical locations and ecosystem conditions, demonstrating the inherent difficulty of accurately representing all ecosystems with a single set of formulas. This variation underscores the critical importance of the DNDC model's source code, which researchers frequently modify to better suit specific locations.

To augment the practicality and applicability of the model, it is crucial to promote the sharing of the DNDC model's source code within the scientific community. This openness would empower independent researchers to verify the model's precision, pinpoint potential errors or shortcomings, and implement necessary adjustments or enhancements to the model. Such sharing practices foster transparency, reproducibility, and credibility, all of which are vital for the advancement of science and for making informed decisions. Ultimately, the DNDC model, with its inherent strengths and weaknesses, can see a significant improvement in its performance through a willingness to share and adapt its foundational source code.

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| Publications | Model Version | Functions |
| --- | --- | --- |
| C. Li et al. (1992) | DNDC v. 1.0-7.0 | There are three basic sub-models in the DNDC model: the soil climate/water heat flux sub-model, the organic carbon decomposition process sub-model, and the denitrification sub-model (which includes only one equation for nitrification when there is no crop growth) . |
| C. Li et al. (1994) | DNDC v. 7.1 | The initial version was improved by adding a plant growth process submodel and a land management use submodel. |
| C. Li et al. (2000) | PnET-N-DNDC | Integrated the models of photosynthesis, evapotranspiration, DNDC, and nitrification, replacing crop growth with forest growth, which can predict the emissions of $N_2O$ and NO in forest soils. Introduced the concept of "anaerobic balloon" and considered the influence of freezing and thawing on soil moisture. |
| Li, (2000) and Li et al. (2000) | DNDC v. 8.0 | A new two-component model framework was developed in the PnET-N-DNDC model, incorporating a submodel that simulates fermentation processes using soil redox potential. The model integrates the anaerobic chamber concept along with freeze-thaw effects. |
| Y. Zhang, Li, Zhou, et al. (2002) | Crop-DNDC | Simulating crop growth through physiological processes under water and nitrogen stress, a new phenology crop submodel incorporating the initial version submodels (decomposition, nitrification, and denitrification) was introduced. |
| Y. Zhang, Li, Zhou, et al. (2002) | DNDC v. 8.2 | The new phenology crop submodel was introduced into the DNDC model as a replacement for the empirical crop growth submodel added in 1994. The new phenology crop physiological and ecological model requires more and finer plant growth parameters, while the simulated results are more accurate. |
| Y. Zhang, Li, Trettin, et al. (2002) | Wetland-DNDC | To predict $CO_2$ and $CH_4$ emissions in wetland ecosystems, we integrated the PnET-N-DNDC and FLATWODS models that are suitable for such ecosystems. We introduced dynamic changes in water levels and modified soil properties and climatic conditions. The resulting model comprises four submodels: hydrological conditions, soil temperature, plant growth, and soil carbon dynamics. |
| Brown et al. (2002) | UK-DNDC | Adapting the DNDC model for simulating UK ecosystems. |

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| C. Li, Cui, et al. (2004) | DNDC v. 8.5 | Modified the concept of "anaerobic gas vesicle" by incorporating the Nernst equation and combining it with the Michaelis-Menten equation. |
| Saggar et al. (2004) | NZ-DNDC | Modified the model of annual crops to that of perennial grass growth, quantified the nitrogen input from herbivore excreta, replaced the Thorthwaite equation with the Priestley-Taylor equation to calculate potential soil evapotranspiration, and changed the order of soil water infiltration and drainage to simulate the $N_2O$ emission patterns from New Zealand grassland. |
| C. Li, Mosier, et al. (2004) | DNDC-Rice | Modified the DNDC model to make it applicable to rice paddy ecosystems. Further improvements were made by Rafique et al. (2011) in Indian rice paddies. Fumoto et al. (2008) enhanced and integrated the MACROS implementation. |
| C. Li et al. (2005) | Forest-DNDC | Integrated the PnET and DNDC models for both dryland and wetland forest ecosystems. |
| Kiese et al. (2005) | Forest-DNDC-Tropica | Modified the PnET-N-DNDC model to make it applicable to tropical rainforest ecosystems. |
| Neufeldt et al. (2006) | EFEM-DNDC | Coupling EFEM and DNDC v8.0 to simulate greenhouse gas emissions from typical livestock and production systems in Baden-Württemberg, Germany, using a GIS-coupled economic-ecological system model. |
| C. Li et al. (2006) | DNDC v. 9.0 | Introducing free ammonium kinetics and improving the leaching of nitrification and nitrate to optimize the accuracy of the model simulation. |
| Beheydt (2006) | BE-DNDC | Combining DNDC v8.3P with regional data from Belgium to calculate the regional framework for $N_2O$ emissions from intensive agricultural land. |
| Fumoto et al. (2008) | DNDC-Rice | Making the DNDC-Rice model capable of simulating rice paddies with different flooding regimes. |
| Leip et al. (2008) | DNDC-Europe | Integrating CAPRI into DNDC to assess the impact of agricultural environmental policies on greenhouse gas emissions. |
| Grote et al. (2009) and Grote et al. (2011) | Mobile-DNDC | Linking MoiBiLE to one-dimensional ecosystem models such as DNDC to obtain the most suitable model combination for specific research tasks. MoBiLE-DNDC was adapted by Wolf et al. (2012). |
| W. N. Smith et al. (2010) | DNDC v. 9.3 | Improve the estimation of soil evaporation in the DNDC model. |
| Kröbel et al. (2011) | DNDC-CSW | Incorporate the CSW (Canadian spring wheat) empirical sub-model into the DNDC model to |

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| | | more accurately estimate the growth and nitrogen uptake of spring wheat in Canadian agricultural ecosystems. |
| Y. Zhang et al. (2012) | NEST-DNDC | Develop an integrated approach to quantify $CH_4$ emissions under permafrost conditions and combine DNDC with NEST. |
| C. Li et al. (2012) | Manure-DNDC | Predict GHG and $NH_3$ emissions from manure generated by farms, and modify DNDC to represent the manure lifecycle on farms. |
| C. Li et al. (2012) | DNDC v. 9.4 | Introduce the soil $NH_3$ algorithm developed by Manure-DNDC. |
| Haas et al. (2013) | Landscape-DNDC | Use DNDC and Forest-DNDC as a universal soil biogeochemical module to simulate multiple ecosystems. |
| Z. Zhao et al. (2014) | DNDC v. 9.5 | The DNDC v9.5 version is the current version, which includes optimized modules for crop growth simulation, hydrology, greenhouse gas emission-related parameters, etc., to meet the needs of greenhouse gas mitigation research. |
| Katayanagi et al. (2017) | DNDC v. 9.5 | Revised the emission factors (EFs) to consider the effects of $CH_4$ emissions. |
| Dutta et al. (2018) | DNDC v. 9.5 | The model mechanism was calibrated under two strongly contrasting soil textures (sandy and clay soils) . The calculation of soil temperature driven by soil thermal conductivity and heat capacity was improved, and the surface soil temperature mechanism of DNDC was improved to improve greenhouse gas prediction. |
| Amponsah et al. (2019) | DNDC-OP | Combine PAH degradation rates with dynamic soil, vegetation, and climate factors (such as soil moisture and temperature) to simulate the degradation dynamics of PAHs in soil at abandoned oil and gas well sites. |
| Dubache et al. (2019) | DNDC v. 9.5 | The regulation of soil moisture on urea hydrolysis was increased, and the temperature regulation parameterization of this process was calibrated. The volatilization coefficient of $NH_3$ released from soil water to the atmosphere above bare soil or tree canopy was redefined. The regulation of soil texture (expressed as clay fraction) and the regulation of wet and/or dry canopy were redefined, as well as the parameterization of wind speed, soil temperature, and moisture regulation. |
| He et al. (2019) | DNDC v. 9.5 | The DNDC model was modified to improve alfalfa growth simulation. |
| S. Li et al. (2019) | DNDC v. 9.5 | The calculation of soil moisture was modified, and |

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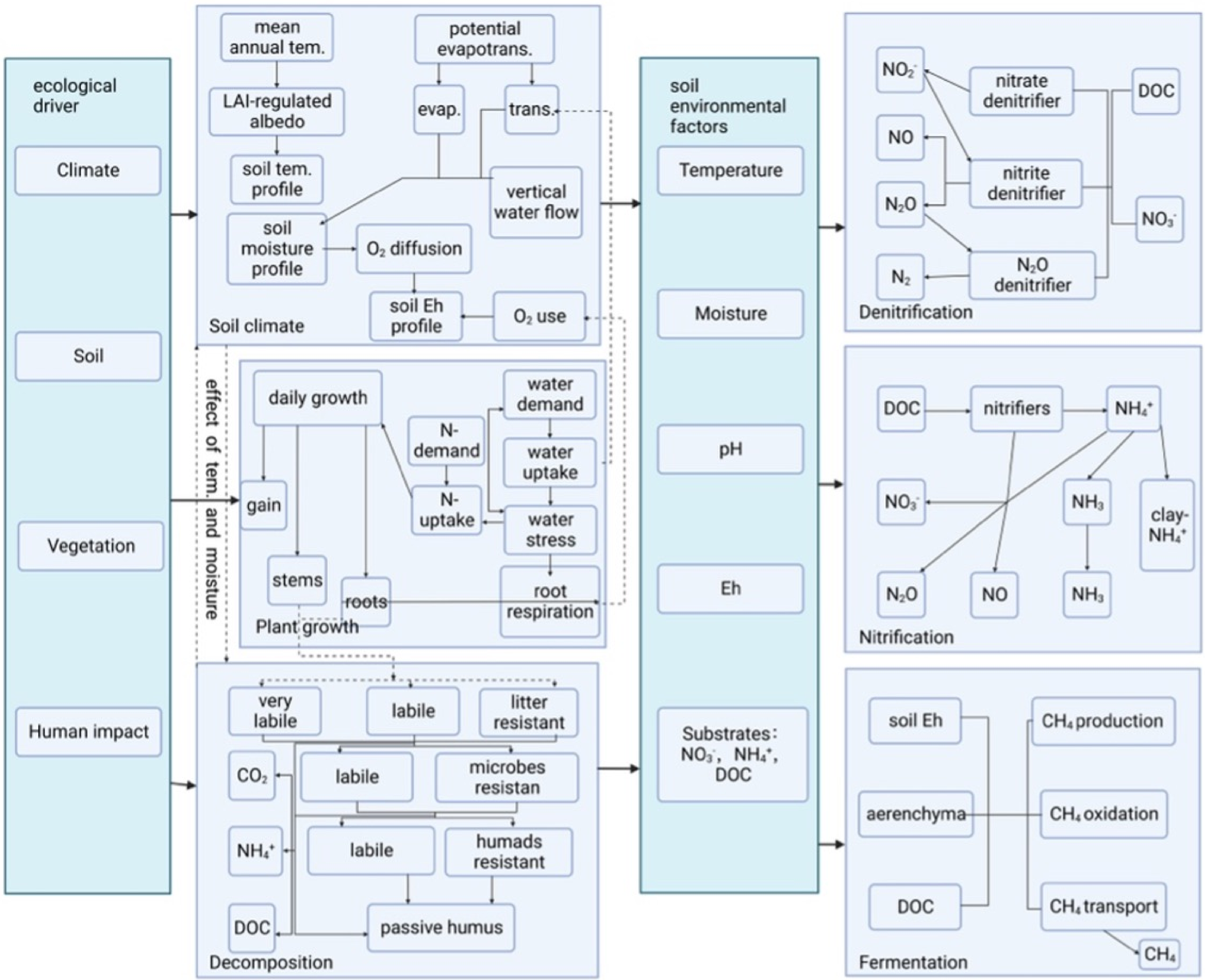
| | | parameterization for temperature regulation was designed when defining the rate constant for ammonium bicarbonate (ABC) decomposition and $NH_3$ release to the atmosphere. The regulation of texture on $NH_3$ volatilization from soil was re-parameterized. An adaptation coefficient was added for an unknown regulatory factor that affects the volatilization of dissolved $NH_3$. In addition, pedo-transfer functions (PTFs) were introduced into the model to estimate soil hydraulic parameters using physical and chemical properties as model inputs. |
| Cui & Wang (2019) | DNDC v. 9.5 | The original DNDC model was modified to better represent rainfall-snowfall partitioning, snow cover, and soil freeze-thaw cycles, thereby improving soil temperature simulation, particularly predicting soil temperature and greenhouse gas emissions in cold regions with snow cover during winter. |
| W. Smith et al. (2020) | DNDC v. 9.5 | The soil hydrological framework of DNDC was strengthened, including a new mechanized tile drainage submodel, improved water flux, root growth dynamics, and deeper heterogeneous soil profiles. |

| Publications | Ecosystem | Simulation parameter | Region |
| --- | --- | --- | --- |
| Du et al. (2011) | Alpine meadow | $N_2O$ | China |
| Kang et al. (2020) | Alpine wetland | SOC | China |
| J. Zhang et al. (2017) | Cropland | Yield | China |
| Jarecki et al. (2018) | Cropland | Yield | Canada |
| S. Li et al. 2019) | Cropland | $NH_3$ | China |
| Dubache et al. (2019) | Cropland | $NH_3$ | UK |
| Abdalla et al. (2020) | Cropland | $N_2O$, Yield | China |
| Jiang et al. (2021) | Cropland | $N_2O$ | Canada |
| Hussain Shah et al. (2021) | Cropland | Salinity | Canada |
| L. Wang et al. (2022) | Cropland | $N_2O$ | China |
| C. Wang et al. (2022) | Cropland | $N_2O$ | China |
| Abdalla et al. (2010) | Farm | $N_2O$ | Ireland |
| Y. Zhang et al. (2018) | Farm | Biomass | China |
| Q. Li et al. (2021) | Farm | $CO_2$, $N_2O$, $CH_4$ | China |
| Dou et al. (2014) | Field | SOC | USA |
| Deng et al. (2016) | Field | $N_2O$ | USA |
| Wu et al. (2018) | Grassland | SOC | China |
| Schroeck et al. (2019) | Grassland | Reactive N | Austrian |
| Shah et al. (2020) | Grassland | $N_2O$ | UK |
| Z. Zhao, Cao, Sha, et al. (2020) | Paddy | N | China |
| Hwang et al. (2021) | Paddy | $CO_2$, $CH_4$ | Korea |
| Shaukat et al. (2022) | Paddy | $CH_4$ | USA |

| Publications | Ecosystem | Simulation parameter | Region |
|---|---|---|---|
| C. Li et al. (1994) | Cropland | $N_2O$ | USA |
| C. Li et al. (1996) | Cropland | $N_2O$ | USA |
| C. Li et al. (2001) | Cropland | $N_2O$ | China |
| D. Giltrap et al. (2008) | Cropland | $N_2O$ | New |
| Qiu et al. (2011) | Cropland | $NO_3$ | China |
| Kesik et al. (2005) | Forest | $N_2O$, NO | Europe |
| C. Li, Cui, et al. (2004) | Paddy | $CO_2$, $N_2O$, $CH_4$ | China |
| Pathak et al. (2006) | Paddy | CO2, $N_2O$, $CH_4$ | India |
| Yu et al. (2011) | Paddy | $N_2O$, $CH_4$ | China |
| X. Xu et al. (2011) | Paddy | SOC, $N_2O$, $CH_4$ | China |
| Y. Zhang et al. (2011) | Paddy | $CH_4$ | China |
| Z. Wang et al. (2020) | Paddy | N, $CH_4$ | China |
| Z. Zhao, Cao, Deng, et al. (2020) | Paddy | $N_2O$, $CH_4$ | China |

**Figure 1.**



ecological driver
Climate
Soil
Vegetation
Human impact
mean annual tem.
LAI-regulated albedo
soil tem. profile
soil moisture profile
potential evapotrans.
evap.
trans.
vertical water flow
O₂ diffusion
soil Eh profile
O₂ use
Soil climate
effect of tem. and moisture
daily growth
gain
stems
roots
N-demand
N-uptake
water demand
water uptake
water stress
root respiration
Plant growth
very labile
labile
litter resistant
CO₂
labile
microbes resistan
NH₄⁺
labile
humads resistant
DOC
passive humus
Decomposition
soil environmental factors
Temperature
Moisture
pH
Eh
Substrates: NO₃⁻, NH₄⁺, DOC
NO₂⁻
NO
N₂O
N₂
nitrate denitrifier
nitrite denitrifier
N₂O denitrifier
DOC
NO₃⁻
Denitrification
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NO
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Nitrification
soil Eh
aerenchyma
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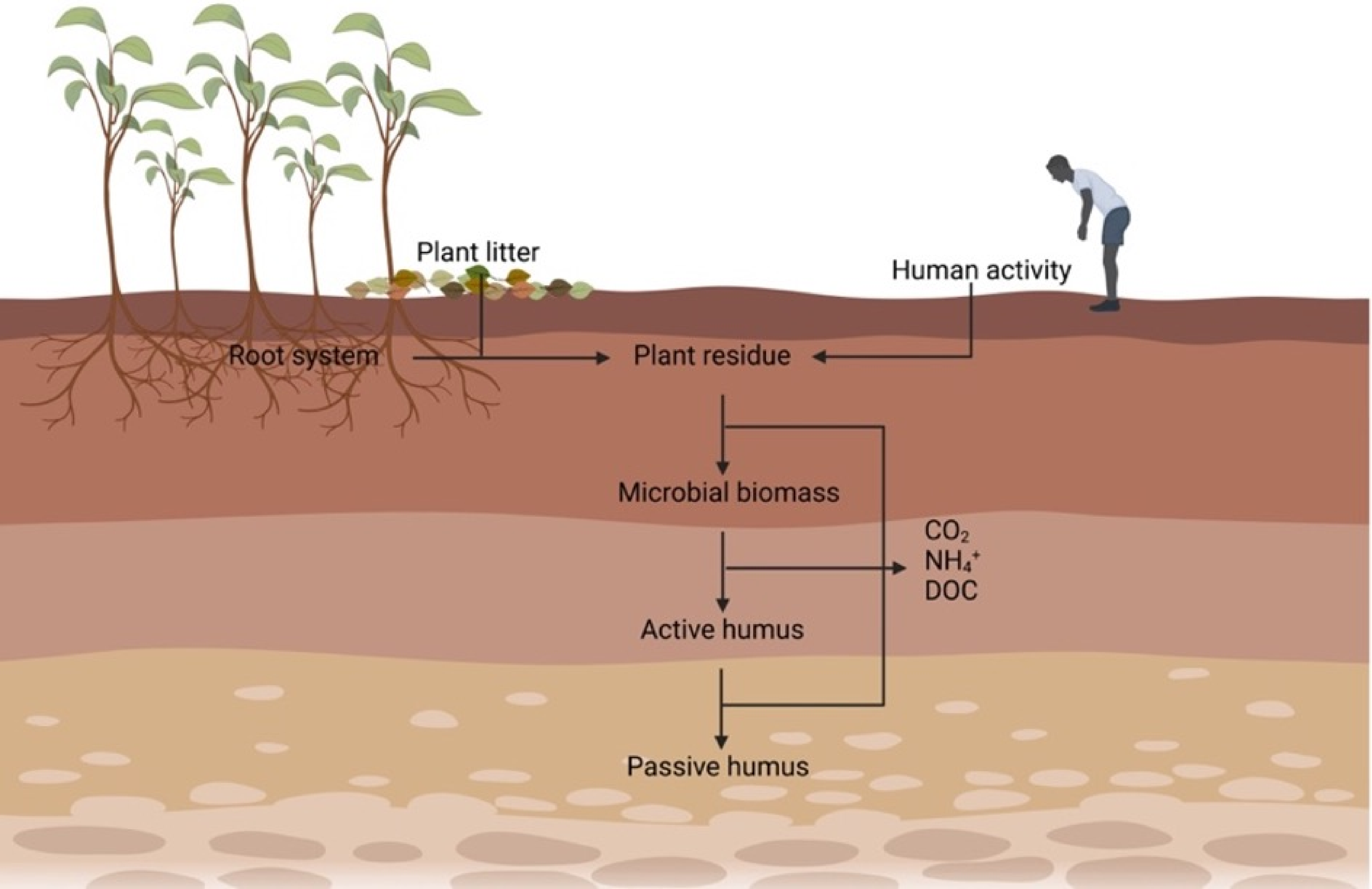
CH₄ production
CH₄ oxidation
CH₄ transport
CH₄
Fermentation

**Figure 2.**



Plant litter
Human activity
Root system
Plant residue
Microbial biomass
$CO_2$
$NH_4^+$
DOC
Active humus
Passive humus