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

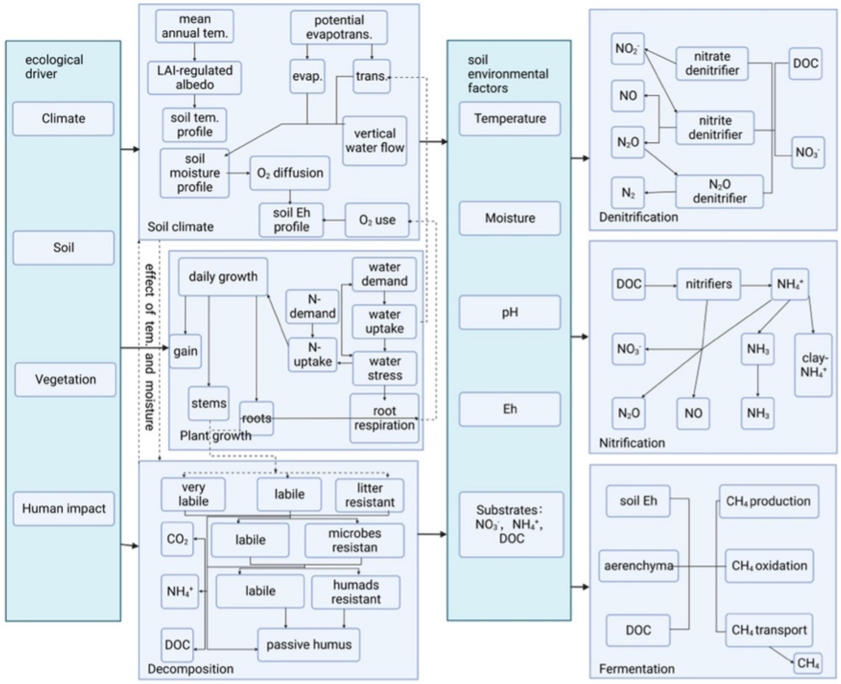
Weipeng Gong[1], Zong Wang[2], Qin Zhang[1], and Tianxiang Yue[3]

[1]Key Laboratory of Agricultural Resources and Ecology in Poyang Lake Watershed of Ministry of Agriculture and Rural Affairs in China
[2]College of Forestry, Beijing Forestry University
[3]Institute of Geographical Sciences and Natural Resources Research, China

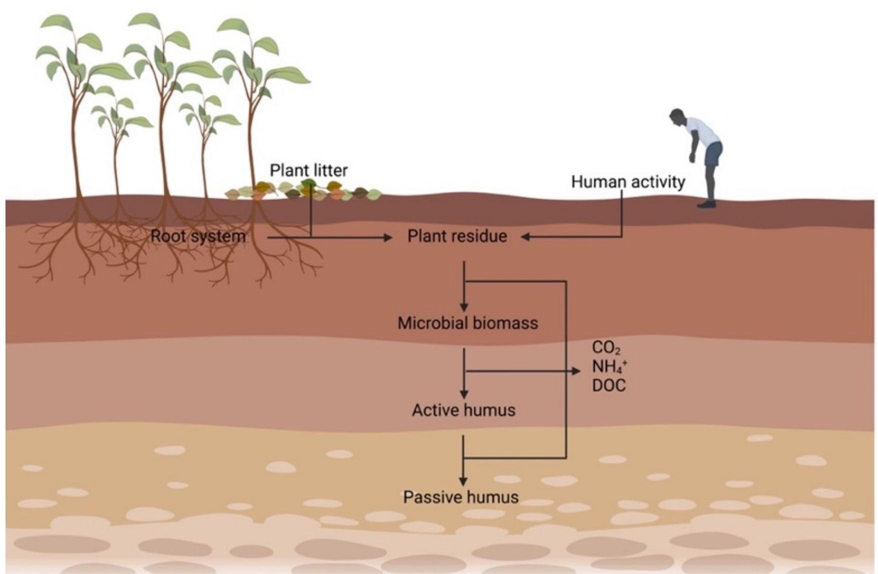
September 11, 2023

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.



ecological driver
Climate
Soil
Vegetation
Human impact
mean annual tem.
potential evapotrans.
LAI-regulated albedo
evap.
trans.
soil tem. profile
vertical water flow
soil moisture profile
O_2 diffusion
soil Eh profile
O_2 use
Soil climate
effect of tem. and moisture
daily growth
water demand
N-demand
water uptake
gain
N-uptake
water stress
stems
roots
root respiration
Plant growth
very labile
labile
litter resistant
CO_2
labile
microbes resistan
NH_4^+
labile
humads resistant
DOC
passive humus
Decomposition
soil environmental factors
Temperature
Moisture
pH
Eh
Substrates: NO_3^-, NH_4^+, DOC
NO_2^-
nitrate denitrifier
DOC
NO
nitrite denitrifier
N_2O
NO_3^-
N_2
N_2O denitrifier
Denitrification
DOC
nitrifiers
NH_4^+
NO_3^-
NH_3
clay-NH_4^+
N_2O
NO
NH_3
Nitrification
soil Eh
CH_4 production
aerenchyma
CH_4 oxidation
DOC
CH_4 transport
CH_4
Fermentation



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

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

Weipeng Gong[1], Zong Wang[2,3], Qin Zhang[1], Tianxiang Yue[1]

[1]Jiangxi Agricultural University, Nanchang, Jiangxi Province, China.

[2]College of Forestry, Precision Forestry Key Laboratory of Beijing, Beijing Forestry University, Beijing, China.

[3]State Key Laboratory of Resources and Environment Information System, Institute of Geographical Science and Natural Resources Research, Chinese Academy of Sciences, Beijing, China.

Corresponding author: Tianxiang Yue（yue@lreis.ac.cn）

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)

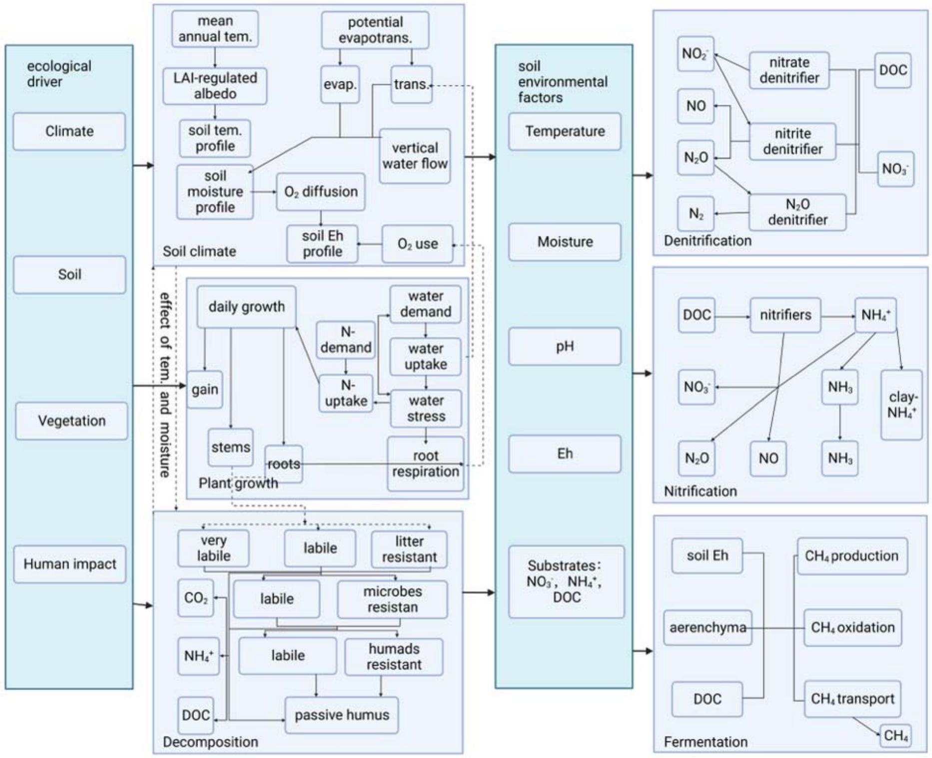


Fig. 1 The scientific structure of the DNDC model

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

		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

		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

		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.

139

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**.

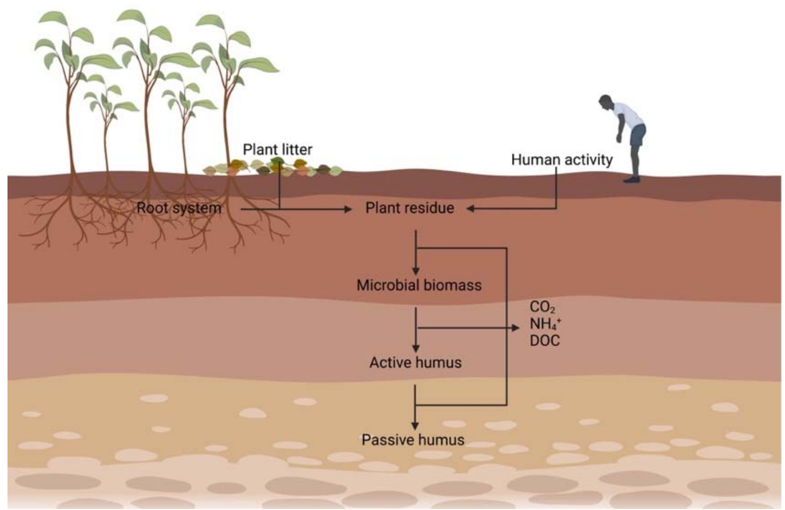


Fig 2 Soil carbon dynamics

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.

7 References

Abdalla, M., Jones, M., Yeluripati, J., Smith, P., Burke, J., & Williams, M. (2010). Testing DayCent and DNDC model simulations of N2O fluxes and assessing the impacts of climate change on the gas flux and biomass production from a humid pasture. *Atmospheric Environment*, *44*(25), 2961–2970. https://doi.org/10.1016/j.atmosenv.2010.05.018

Abdalla, M., Song, X., Ju, X., Topp, C. F. E., & Smith, P. (2020). Calibration and validation of the DNDC model to estimate nitrous oxide emissions and crop productivity for a summer maize-winter wheat double cropping system in Hebei, China. *Environmental Pollution*, *262*, 114199. https://doi.org/10.1016/j.envpol.2020.114199

Afzali, S. F., Azad, B., Golabi, M. H., & Francaviglia, R. (2019). Using RothC Model to Simulate Soil Organic Carbon Stocks under Different Climate Change Scenarios for the Rangelands of the Arid Regions of Southern Iran. *Water*, *11*(10), 2107. https://doi.org/10.3390/w11102107

Amponsah, N. Y., Wang, J., & Zhao, L. (2019). Modelling PAH Degradation in Contaminated Soils in Canada using a Modified Process-Based Model (DNDC). *Soil Science Society of America Journal*, *83*(3), 605–613. https://doi.org/10.2136/sssaj2018.11.0435

Beah, A., Kamara, A. Y., Jibrin, J. M., Akinseye, F. M., Tofa, A. I., & Adam, Adam. M. (2020).

Simulating the Response of Drought–Tolerant Maize Varieties to Nitrogen Application in Contrasting Environments in the Nigeria Savannas Using the APSIM Model. *Agronomy*, *11*(1), 76. https://doi.org/10.3390/agronomy11010076

Beheydt, D. (2006). *Nitrous oxide emission from agricultural soils: Experimental approach and simulation* [Dissertation, Ghent University]. http://hdl.handle.net/1854/LU-8646870

Brown, L., Syed, B., Jarvis, S. C., Sneath, R. W., Phillips, V. R., Goulding, K. W. T., & Li, C. (2002). Development and application of a mechanistic model to estimate emission of nitrous oxide from UK agriculture. *Atmospheric Environment*, *36*(6), 917–928. https://doi.org/10.1016/S1352-2310(01)00512-X

Cao, M., & Woodward, F. I. (1998). Dynamic responses of terrestrial ecosystem carbon cycling to global climate change. *Nature*, *393*(6682), 249–252.

Chen, H., Zhu, Q., Peng, C., Wu, N., Wang, Y., Fang, X., Jiang, H., Xiang, W., Chang, J., & Deng, X. (2013). Methane emissions from rice paddies natural wetlands, lakes in China: Synthesis new estimate. *Global Change Biology*, *19*(1), 19–32.

Cui, G., & Wang, J. (2019). Improving the DNDC biogeochemistry model to simulate soil temperature and emissions of nitrous oxide and carbon dioxide in cold regions. *Science of The Total Environment*, *687*, 61–70. https://doi.org/10.1016/j.scitotenv.2019.06.054

Del Grosso, S. J., Parton, W. J., Mosier, A. R., Walsh, M. K., Ojima, D. S., & Thornton, P. E. (2006). DAYCENT national-scale simulations of nitrous oxide emissions from cropped soils in the United States. *Journal of Environmental Quality*, *35*(4), 1451–

1460.

Deng, Q., Hui, D., Wang, J., Yu, C.-L., Li, C., Reddy, K. C., & Dennis, S. (2016). Assessing the impacts of tillage and fertilization management on nitrous oxide emissions in a cornfield using the DNDC model: MODELING N $_2$ O EMISSION IN A CORNFIELD. *Journal of Geophysical Research: Biogeosciences*, *121*(2), 337–349. https://doi.org/10.1002/2015JG003239

Dou, F., Wight, J. P., Wilson, L. T., Storlien, J. O., & Hons, F. M. (2014). Simulation of biomass yield and soil organic carbon under bioenergy sorghum production. *PLoS One*, *9*(12), e115598.

Du, Y., Cui, X., Cao, G., Zhao, X., & Yang, G. (2011). *Simulating N2O emission from Kobresia humilis Serg. Alpine meadow on Tibetan Plateau with the DNDC model*.

Dubache, G., Li, S., Zheng, X., Zhang, W., & Deng, J. (2019). Modeling ammonia volatilization following urea application to winter cereal fields in the United Kingdom by a revised biogeochemical model. *Science of The Total Environment*, *660*, 1403–1418. https://doi.org/10.1016/j.scitotenv.2018.12.407

Dutta, B., Grant, B. B., Congreves, K. A., Smith, W. N., Wagner-Riddle, C., VanderZaag, A. C., Tenuta, M., & Desjardins, R. L. (2018). Characterising effects of management practices, snow cover, and soil texture on soil temperature: Model development in DNDC. *Biosystems Engineering*, *168*, 54–72. https://doi.org/10.1016/j.biosystemseng.2017.02.001

Fillery, I., Simpson, J., & De Datta, S. (1986). Contribution of ammonia volatilization to total nitrogen loss after applications of urea to wetland rice fields. *Fertilizer Research*, *8*(3), 193–202. https://doi.org/10.1007/BF01048620

Frank, S., Havlík, P., Stehfest, E., van Meijl, H., Witzke, P., Pérez-Domínguez, I., van Dijk, M., Doelman, J. C., Fellmann, T., & Koopman, J. F. (2019). Agricultural non-CO2 emission reduction potential in the context of the 1.5 C target. *Nature Climate Change*, *9*(1), 66–72.

Fumoto, T., Kobayashi, K., Li, C., Yagi, K., & Hasegawa, T. (2008). Revising a process-based biogeochemistry model (DNDC) to simulate methane emission from rice paddy fields under various residue management and fertilizer regimes: MODELING METHANE EMISSION FROM RICE FIELDS. *Global Change Biology*, *14*(2), 382–402. https://doi.org/10.1111/j.1365-2486.2007.01475.x

Gilhespy, S. L., Anthony, S., Cardenas, L., Chadwick, D., Del Prado, A., Li, C., Misselbrook, T., Rees, R. M., Salas, W., Sanz-Cobena, A., Smith, P., Tilston, E. L., Topp, C. F. E., Vetter, S., & Yeluripati, J. B. (2014). First 20 years of DNDC (DeNitrification DeComposition): Model evolution. *Ecological Modelling*, *292*, 51–62. https://doi.org/10.1016/j.ecolmodel.2014.09.004

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

Giltrap, D., Saggar, S., Li, C., & Wilde, H. (2008). Using the NZ–DNDC model to estimate agricultural N2O emissions in the Manawatu–Wanganui region. *Plant and Soil*, *309*(1), 191–209. https://doi.org/10.1007/s11104-007-9527-7

Grote, R., Korhonen, J., & Mammarella, I. (2011). Challenges for evaluating process-based models of gas exchange at forest sites with fetches of various species. *Forest Systems*, *20*(3), 389–406.

Grote, R., Lavoir, A.-V., Rambal, S., Staudt, M., Zimmer, I., & Schnitzler, J.-P. (2009). Modelling the drought impact on monoterpene fluxes from an evergreen Mediterranean forest canopy. *Oecologia*, *160*, 213–223.

Haas, E., Klatt, S., Fröhlich, A., Kraft, P., Werner, C., Kiese, R., Grote, R., Breuer, L., & Butterbach-Bahl, K. (2013). LandscapeDNDC: A process model for simulation of biosphere–atmosphere–hydrosphere exchange processes at site and regional scale. *Landscape Ecology*, *28*(4), 615–636. https://doi.org/10.1007/s10980-012-9772-x

Hastings, A. F., Wattenbach, M., Eugster, W., Li, C., Buchmann, N., & Smith, P. (2010). Uncertainty propagation in soil greenhouse gas emission models: An experiment using the DNDC model and at the Oensingen cropland site. *Agriculture, Ecosystems & Environment*, *136*(1–2), 97–110. https://doi.org/10.1016/j.agee.2009.11.016

He, W., Grant, B. B., Smith, W. N., VanderZaag, A. C., Piquette, S., Qian, B., Jing, Q., Rennie, T. J., Bélanger, G., Jégo, G., & Deen, B. (2019). Assessing alfalfa production under historical and future climate in eastern Canada: DNDC model development and application. *Environmental Modelling & Software*, *122*, 104540. https://doi.org/10.1016/j.envsoft.2019.104540

Hussain Shah, S. H., Wang, J., Hao, X., & Thomas, B. W. (2021). Modeling the effect of salt-affected soil on water balance fluxes and nitrous oxide emission using modified DNDC. *Journal of Environmental Management*, *280*, 111678. https://doi.org/10.1016/j.jenvman.2020.111678

Hwang, W., Kim, C., Cho, K., & Hyun, S. (2021). Characteristics of greenhouse gas emissions from rice paddy fields in South Korea under climate change scenario RCP-8.5 using the DNDC model. *Pedosphere*, *31*(2), 332–341. https://doi.org/10.1016/S1002-0160(20)60068-6

Jiang, R., Yang, J. Y., Drury, C. F., He, W., Smith, W. N., Grant, B. B., He, P., & Zhou, W. (2021). Assessing the impacts of diversified crop rotation systems on yields and nitrous oxide emissions in Canada using the DNDC model. *Science of The Total Environment*, *759*, 143433. https://doi.org/10.1016/j.scitotenv.2020.143433

Kang, X., Li, Y., Wang, J., Yan, L., Zhang, X., Wu, H., Yan, Z., Zhang, K., & Hao, Y. (2020). Precipitation and temperature regulate the carbon allocation process in alpine wetlands: Quantitative simulation. *Journal of Soils and Sediments*, *20*(9), 3300–3315. https://doi.org/10.1007/s11368-020-02643-x

Katayanagi, N., Fumoto, T., Hayano, M., Shirato, Y., Takata, Y., Leon, A., & Yagi, K. (2017). Estimation of total CH4 emission from Japanese rice paddies using a new estimation method based on the DNDC-Rice simulation model. *Science of The Total Environment*, *601–602*, 346–355. https://doi.org/10.1016/j.scitotenv.2017.05.090

Katayanagi, N., Furukawa, Y., Fumoto, T., & Hosen, Y. (2012). Validation of the DNDC-Rice model by using CH4 and N2O flux data from rice cultivated in pots under alternate wetting and drying irrigation management. *Soil Science and Plant Nutrition*, *58*(3), 360–372.

Kesik, M., Ambus, P., Baritz, R., Brüggemann, N., Butterbach-Bahl, K., Damm, M., Duyzer, J., Horváth, L., Kiese, R., & Kitzler, B. (2005). Inventories of N 2 O and NO emissions from European forest soils. *Biogeosciences*, *2*(4), 353–375.

Kiese, R., Li, C., Hilbert, D. W., Papen, H., & Butterbach-Bahl, K. (2005). Regional application of PnET-N-DNDC for estimating the N2O source strength of tropical rainforests in the Wet Tropics of Australia. *Global Change Biology*, *11*(1), 128–144. https://doi.org/10.1111/j.1365-2486.2004.00873.x

Kröbel, R., Smith, W., Grant, B., Desjardins, R., Campbell, C., Tremblay, N., Li, C., Zentner, R., & McConkey, B. (2011). Development and evaluation of a new Canadian spring wheat sub-model for DNDC. *Canadian Journal of Soil Science*, *91*(4), 503–520. https://doi.org/10.4141/cjss2010-059

Leip, A., Marchi, G., Koeble, R., Kempen, M., Britz, W., & Li, C. (2008). Linking an economic model for European agriculture with a mechanistic model to estimate nitrogen and carbon losses from arable soils in Europe. *Biogeosciences*, *5*(1), 73–94. https://doi.org/10.5194/bg-5-73-2008

Li, C. (2016). *Biogeochemistry: Scientific fundamentals and modelling approach*. Tsinghua University Press, Beijing.

Li, C., Aber, J., Stange, F., Butterbach-Bahl, K., & Papen, H. (2000). A process-oriented model of N2O and NO emissions from forest soils: 1. Model development. *Journal of Geophysical Research: Atmospheres*, *105*(D4), 4369–4384.

Li, C., Cui, J., Sun, G., & Trettin, C. (2004). Modeling impacts of management on carbon sequestration and trace gas emissions in forested wetland ecosystems. *Environmental Management*, *33*, S176–S186.

Li, C., Farahbakhshazad, N., Jaynes, D. B., Dinnes, D. L., Salas, W., & McLaughlin, D.

(2006). Modeling nitrate leaching with a biogeochemical model modified based on observations in a row-crop field in Iowa. *Ecological Modelling*, *196*(1–2), 116–130.

Li, C., Frolking, S., Crocker, G. J., Grace, P. R., Klír, J., Körchens, M., & Poulton, P. R. (1997). Simulating trends in soil organic carbon in long-term experiments using the DNDC model. *Geoderma*, *81*(1–2), 45–60. https://doi.org/10.1016/S0016-7061(97)00080-3

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.

Li, C., Frolking, S., & Harriss, R. (1994). Modeling carbon biogeochemistry in agricultural soils. *Global Biogeochemical Cycles*, *8*(3), 237–254. https://doi.org/10.1029/94GB00767

Li, C., Mosier, A., Wassmann, R., Cai, Z., Zheng, X., Huang, Y., Tsuruta, H., Boonjawat, J., & Lantin, R. (2004). Modeling greenhouse gas emissions from rice-based production systems: Sensitivity and upscaling. *Global Biogeochemical Cycles*, *18*(1).

Li, C., Narayanan, V., & Harriss, R. C. (1996). Model estimates of nitrous oxide emissions from agricultural lands in the United States. *Global Biogeochemical Cycles*, *10*(2), 297–306.

Li, C. S. (2000). Modeling trace gas emissions from agricultural ecosystems. *Methane Emissions from Major Rice Ecosystems in Asia*, 259–276.

Li, C., Salas, W., Zhang, R., Krauter, C., Rotz, A., & Mitloehner, F. (2012). Manure-DNDC: A biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. *Nutrient Cycling in Agroecosystems*, *93*(2), 163–200. https://doi.org/10.1007/s10705-012-9507-z

Li, C., Trettin, C., Sun, G., McNulty, S., & Butterbach-Bahl, K. (2005). Modeling carbon and nitrogen biogeochemistry in forest ecosystems. *In: 3rd International Nitrogen Conference: 893-898*.

Li, C., Zhuang, Y., Cao, M., Crill, P., Dai, Z., Frolking, S., Moore, B., Salas, W., Song, W., & Wang, X. (2001). Comparing a process-based agro-ecosystem model to the IPCC methodology for developing a national inventory of N2O emissions from arable lands in China. *Nutrient Cycling in Agroecosystems*, *60*, 159–175.

Li, H., Wang, L., Li, J., Gao, M., Zhang, J., Zhang, J., Qiu, J., Deng, J., Li, C., & Frolking, S. (2017). The development of China-DNDC and review of its applications for sustaining Chinese agriculture. *Ecological Modelling*, *348*, 1–13. https://doi.org/10.1016/j.ecolmodel.2017.01.003

Li, Q., Gao, M., & Li, J. (2021). Carbon emissions inventory of farm size pig husbandry combining Manure-DNDC model and IPCC coefficient methodology. *Journal of Cleaner Production*, *320*, 128854. https://doi.org/10.1016/j.jclepro.2021.128854

Li, S., Zheng, X., Zhang, W., Han, S., Deng, J., Wang, K., Wang, R., Yao, Z., & Liu, C. (2019). Modeling ammonia volatilization following the application of synthetic fertilizers to cultivated uplands with calcareous soils using an improved DNDC biogeochemistry model. *Science of The Total Environment*, *660*, 931–946. https://doi.org/10.1016/j.scitotenv.2018.12.379

Liu, L., Zhang, X., Xu, W., Liu, X., Li, Y., Wei, J., Wang, Z., & Lu, X. (2020). Ammonia volatilization as the major nitrogen loss pathway in dryland agro-ecosystems. *Environmental Pollution*, *265*, 114862.

Luo, J., Chen, Y., Zhu, W., & Zhou, P. (2013). Modeling climate change effects on soil respiration in three different stages of primary succession in deglaciated region on Gongga Mountain, China. *Scandinavian Journal of Forest Research*, *28*(4), 363–372. https://doi.org/10.1080/02827581.2012.735696

Luo, T., Liu, W., Xia, D., Xia, L., Guo, T., Ma, Y., Xu, W., & Hu, Y. (2022). Effects of land use types on soil erodibility in a small karst watershed in western Hubei. *PeerJ*, *10*, e14423. https://doi.org/10.7717/peerj.14423

Macharia, J. M., Ngetich, F. K., & Shisanya, C. A. (2021). Parameterization, calibration and validation of the DNDC model for carbon dioxide, nitrous oxide and maize crop performance estimation in East Africa. *Heliyon*, *7*(5), e06977. https://doi.org/10.1016/j.heliyon.2021.e06977

Neufeldt, H., Schäfer, M., Angenendt, E., Li, C., Kaltschmitt, M., & Zeddies, J. (2006). Disaggregated greenhouse gas emission inventories from agriculture via a coupled economic-ecosystem model. *Agriculture, Ecosystems & Environment*, *112*(2–3), 233–240.

Oreskes, N. (2003). The role of quantitative models in science. *Models in Ecosystem Science*, *13*, 27.

Pathak, H., Li, C., & Wassmann, R. (2005). Greenhouse gas emissions from Indian rice fields: Calibration and upscaling using the DNDC model. *Biogeosciences*, *2*(2), 113–123.

Pathak, H., Li, C., Wassmann, R., & Ladha, J. K. (2006). Simulation of Nitrogen Balance in

Rice-Wheat Systems of the Indo-Gangetic Plains. *Soil Science Society of America Journal*, *70*(5), 1612–1622. https://doi.org/10.2136/sssaj2005.0165

Qiu, J., Li, H., Wang, L., Tang, H., Li, C., & Van Ranst, E. (2011). GIS-model based estimation of nitrogen leaching from croplands of China. *Nutrient Cycling in Agroecosystems*, *90*(2), 243–252. https://doi.org/10.1007/s10705-011-9425-5

Rafique, R., Peichl, M., Hennessy, D., & Kiely, G. (2011). Evaluating management effects on nitrous oxide emissions from grasslands using the process-based DeNitrification–DeComposition (DNDC) model. *Atmospheric Environment*, *45*(33), 6029–6039. https://doi.org/10.1016/j.atmosenv.2011.07.046

Saggar, S., Andrew, R. M., Tate, K. R., Hedley, C. B., Rodda, N. J., & Townsend, J. A. (2004). Modelling nitrous oxide emissions from dairy-grazed pastures. *Nutrient Cycling in Agroecosystems*, *68*(3), 243–255. https://doi.org/10.1023/B:FRES.0000019463.92440.a3

Schroeck, A. M., Gaube, V., Haas, E., & Winiwarter, W. (2019). Estimating nitrogen flows of agricultural soils at a landscape level – A modelling study of the Upper Enns Valley, a long-term socio-ecological research region in Austria. *Science of The Total Environment*, *665*, 275–289. https://doi.org/10.1016/j.scitotenv.2019.02.071

Shah, S. H. H., Li, Y., Wang, J., & Collins, A. L. (2020). Optimizing farmyard manure and cattle slurry applications for intensively managed grasslands based on UK-DNDC model simulations. *Science of The Total Environment*, *714*, 136672. https://doi.org/10.1016/j.scitotenv.2020.136672

Shaukat, M., Muhammad, S., Maas, E. D. V. L., Khaliq, T., & Ahmad, A. (2022). Predicting methane emissions from paddy rice soils under biochar and nitrogen addition using DNDC model. *Ecological Modelling*, *466*, 109896. https://doi.org/10.1016/j.ecolmodel.2022.109896

Smith, W., Grant, B., Qi, Z., He, W., VanderZaag, A., Drury, C. F., & Helmers, M. (2020). Development of the DNDC model to improve soil hydrology and incorporate mechanistic tile drainage: A comparative analysis with RZWQM2. *Environmental Modelling & Software*, *123*, 104577. https://doi.org/10.1016/j.envsoft.2019.104577

Smith, W. N., Desjardins, R. L., & Pattey, E. (2000). The net flux of carbon from agricultural soils in Canada 1970-2010: C FLUX IN CANADIAN SOILS. *Global Change Biology*, *6*(5), 557–568. https://doi.org/10.1046/j.1365-2486.2000.00340.x

Smith, W. N., Grant, B. B., Campbell, C. A., McConkey, B. G., Desjardins, R. L., Kröbel, R., & Malhi, S. S. (2012). Crop residue removal effects on soil carbon: Measured and inter-model comparisons. *Agriculture, Ecosystems & Environment*, *161*, 27–38. https://doi.org/10.1016/j.agee.2012.07.024

Smith, W. N., Grant, B. B., Desjardins, R. L., Worth, D., Li, C., Boles, S. H., & Huffman, E. C. (2010). A tool to link agricultural activity data with the DNDC model to estimate GHG emission factors in Canada. *Agriculture, Ecosystems & Environment*, *136*(3–4), 301–309. https://doi.org/10.1016/j.agee.2009.12.008

Syp, A., Faber, A., & Borz, M. (2012). *Simulation of soil organic carbon in long-term experiments in Poland using the DNDC model*.

US-EPA, E. (2006). Global anthropogenic non-CO2 greenhouse gas emissions: 1990–2020. *Appendix AD. Washington, DC, USA: United States Environmental Protection Agency.*

Electricity (Heat) Supply.

Wang, C., Zhao, J., Gao, Z., Feng, Y., Laraib, I., Chen, F., & Chu, Q. (2022). Exploring wheat-based management strategies to balance agricultural production and environmental sustainability in a wheat−maize cropping system using the DNDC model. *Journal of Environmental Management*, *307*, 114445. https://doi.org/10.1016/j.jenvman.2022.114445

Wang, L., Zhang, K., Guo, K., Liu, L., Zhang, T., Xu, M., Yan, X., & Gao, X. (2022). Multifactor effects on the N2O emissions and yield of potato fields based on the DNDC model. *Environmental Science and Pollution Research*, *29*(17), 25448–25460. https://doi.org/10.1007/s11356-021-17700-2

Wang, Y., Cheng, H., Wang, N., Huang, C., Zhang, K., Qiao, B., Wang, Y., & Wen, P. (2023). Trade-Off and Synergy Relationships and Spatial Bundle Analysis of Ecosystem Services in the Qilian Mountains. *Remote Sensing*, *15*(11), 2950. https://doi.org/10.3390/rs15112950

Wang, Z., Zhang, X., Liu, L., Wang, S., Zhao, L., Wu, X., Zhang, W., & Huang, X. (2020). Inhibition of methane emissions from Chinese rice fields by nitrogen deposition based on the DNDC model. *Agricultural Systems*, *184*, 102919. https://doi.org/10.1016/j.agsy.2020.102919

Wang, Z., Zhang, X., Liu, L., Wang, S., Zhao, L., Wu, X., Zhang, W., & Huang, X. (2021). Estimates of methane emissions from Chinese rice fields using the DNDC model. *Agricultural and Forest Meteorology*, *303*, 108368. https://doi.org/10.1016/j.agrformet.2021.108368

Wolf, B., Kiese, R., Chen, W., Grote, R., Zheng, X., & Butterbach-Bahl, K. (2012). Modeling N2O emissions from steppe in Inner Mongolia, China, with consideration of spring thaw and grazing intensity. *Plant and Soil*, *350*(1–2), 297–310. https://doi.org/10.1007/s11104-011-0908-6

Wu, X., Kang, X., Liu, W., Cui, X., Hao, Y., & Wang, Y. (2018). Using the DNDC model to simulate the potential of carbon budget in the meadow and desert steppes in Inner Mongolia, China. *Journal of Soils and Sediments*, *18*(1), 63–75. https://doi.org/10.1007/s11368-017-1737-x

Xu, R., Tian, H., Pan, S., Prior, S. A., Feng, Y., Batchelor, W. D., Chen, J., & Yang, J. (2019). Global ammonia emissions from synthetic nitrogen fertilizer applications in agricultural systems: Empirical and process-based estimates and uncertainty. *Global Change Biology*, *25*(1), 314–326. https://doi.org/10.1111/gcb.14499

Xu, S., Zhao, Y., Shi, X., Yu, D., Li, C., Wang, S., Tan, M., & Sun, W. (2013). Map scale effects of soil databases on modeling organic carbon dynamics for paddy soils of China. *CATENA*, *104*, 67–76. https://doi.org/10.1016/j.catena.2012.10.017

Xu, X., Tang, J., Li, Z., Liu, C., & Han, W. (2011). Global warming potential of emissions from rice paddies in Northeastern China. *Mitigation and Adaptation Strategies for Global Change*, *16*(6), 721–731. https://doi.org/10.1007/s11027-011-9290-1

Yin, S., Zhang, X., Lyu, J., Zhi, Y., Chen, F., Wang, L., Liu, C., & Zhou, S. (2020). Carbon sequestration and emissions mitigation in paddy fields based on the DNDC model: A review. *Artificial Intelligence in Agriculture*, *4*, 140–149. https://doi.org/10.1016/j.aiia.2020.07.002

Yu, D. S., Yang, H., Shi, X. Z., Warner, E. D., Zhang, L. M., & Zhao, Q. G. (2011). Effects of soil spatial resolution on quantifying CH_4 and N_2O emissions from rice fields in the Tai Lake region of China by DNDC model: EFFECTS OF SOIL RESOLUTION ON MODELING. *Global Biogeochemical Cycles*, *25*(2), n/a-n/a. https://doi.org/10.1029/2010GB003825

Yue, Q., Wu, H., Sun, J., Cheng, K., Smith, P., Hillier, J., Xu, X., & Pan, G. (2019). Deriving Emission Factors and Estimating Direct Nitrous Oxide Emissions for Crop Cultivation in China. *Environmental Science & Technology*, *53*(17), 10246–10257. https://doi.org/10.1021/acs.est.9b01285

Zhan, X., Adalibieke, W., Cui, X., Winiwarter, W., Reis, S., Zhang, L., Bai, Z., Wang, Q., Huang, W., & Zhou, F. (2021). Improved Estimates of Ammonia Emissions from Global Croplands. *Environmental Science & Technology*, *55*(2), 1329–1338. https://doi.org/10.1021/acs.est.0c05149

Zhang, F., Li, C., Wang, Z., Glidden, S., Grogan, D. S., Li, X., Cheng, Y., & Frolking, S. (2015). Modeling impacts of management on farmland soil carbon dynamics along a climate gradient in Northwest China during 1981–2000. *Ecological Modelling*, *312*, 1–10. https://doi.org/10.1016/j.ecolmodel.2015.05.006

Zhang, F., Li, C., Wang, Z., & Wu, H. (2006). *Modeling impacts of management alternatives on soil carbon storage of farmland in Northwest China*.

Zhang, J., Hu, K., Li, K., Zheng, C., & Li, B. (2017). Simulating the effects of long-term discontinuous and continuous fertilization with straw return on crop yields and soil organic carbon dynamics using the DNDC model. *Soil and Tillage Research*, *165*, 302–314. https://doi.org/10.1016/j.still.2016.09.004

Zhang, L., Yu, D., Shi, X., Weindorf, D. C., Zhao, L., Ding, W., Wang, H., Pan, J., & Li, C. (2009). Simulation of global warming potential (GWP) from rice fields in the Tai-Lake region, China by coupling 1:50,000 soil database with DNDC model. *Atmospheric Environment*, *43*(17), 2737–2746. https://doi.org/10.1016/j.atmosenv.2009.02.051

Zhang, L., Zhuang, Q., Zhao, Q., He, Y., Yu, D., Shi, X., & Xing, S. (2016). Uncertainty of organic carbon dynamics in Tai-Lake paddy soils of China depends on the scale of soil maps. *Agriculture, Ecosystems & Environment*, *222*, 13–22. https://doi.org/10.1016/j.agee.2016.01.049

Zhang, W., Zhang, F., Qi, J., & Hou, F. (2017). Modeling impacts of climate change and grazing effects on plant biomass and soil organic carbon in the Qinghai–Tibetan grasslands. *Biogeosciences*, *14*(23), 5455–5470. https://doi.org/10.5194/bg-14-5455-2017

Zhang, Y., Li, C., Trettin, C. C., Li, H., & Sun, G. (2002). An integrated model of soil, hydrology, and vegetation for carbon dynamics in wetland ecosystems: SOIL, HYDROLOGY, VEGETATION INTEGRATED MODEL. *Global Biogeochemical Cycles*, *16*(4), 9-1-9–17. https://doi.org/10.1029/2001GB001838

Zhang, Y., Li, C., Zhou, X., & Moore, 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

Zhang, Y., Sachs, T., Li, C., & Boike, J. (2012). Upscaling methane fluxes from closed chambers to eddy covariance based on a permafrost biogeochemistry integrated model. *Global Change Biology*, *18*(4), 1428–1440. https://doi.org/10.1111/j.1365-2486.2011.02587.x

Zhang, Y., Wang, Y. Y., Su, S. L., & Li, C. S. (2011). Quantifying methane emissions from rice paddies in Northeast China by integrating remote sensing mapping with a biogeochemical model. *Biogeosciences*, *8*(5), 1225–1235. https://doi.org/10.5194/bg-8-1225-2011

Zhang, Y., Wu, X., Wang, S., & Niu, H. (2018). The simulation of the vine biomass at different planting ages in Ningxia vineyards using DNDC model. *Acta Ecologica Sinica*, *38*(4), 281–287. https://doi.org/10.1016/j.chnaes.2018.01.012

Zhao, Y., Wang, M., Hu, S., Zhang, X., Ouyang, Z., Zhang, G., Huang, B., Zhao, S., Wu, J., Xie, D., Zhu, B., Yu, D., Pan, X., Xu, S., & Shi, X. (2018). Economics- and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands. *Proceedings of the National Academy of Sciences*, *115*(16), 4045–4050. https://doi.org/10.1073/pnas.1700292114

Zhao, Z., Cao, L., Deng, J., Sha, Z., Chu, C., Zhou, D., Wu, S., & Lv, W. (2020). Modeling CH4 and N2O emission patterns and mitigation potential from paddy fields in Shanghai, China with the DNDC model. *Agricultural Systems*, *178*, 102743. https://doi.org/10.1016/j.agsy.2019.102743

Zhao, Z., Cao, L., Sha, Z., Deng, J., Chu, C., Zhou, D., Wu, S., & Lv, W. (2020). Impacts of fertilization optimization on N loss from paddy fields: Observations and DNDC modeling case study in Shanghai, China. *Soil and Tillage Research*, *199*, 104587.

https://doi.org/10.1016/j.still.2020.104587

Zhao, Z., Zhang, H., Li, C., Zhao, Q., & Cao, L. (2014). Quantifying nitrogen loading from a paddy field in Shanghai, China with modified DNDC model. *Agriculture, Ecosystems & Environment*, *197*, 212–221. https://doi.org/10.1016/j.agee.2014.08.002

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.

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

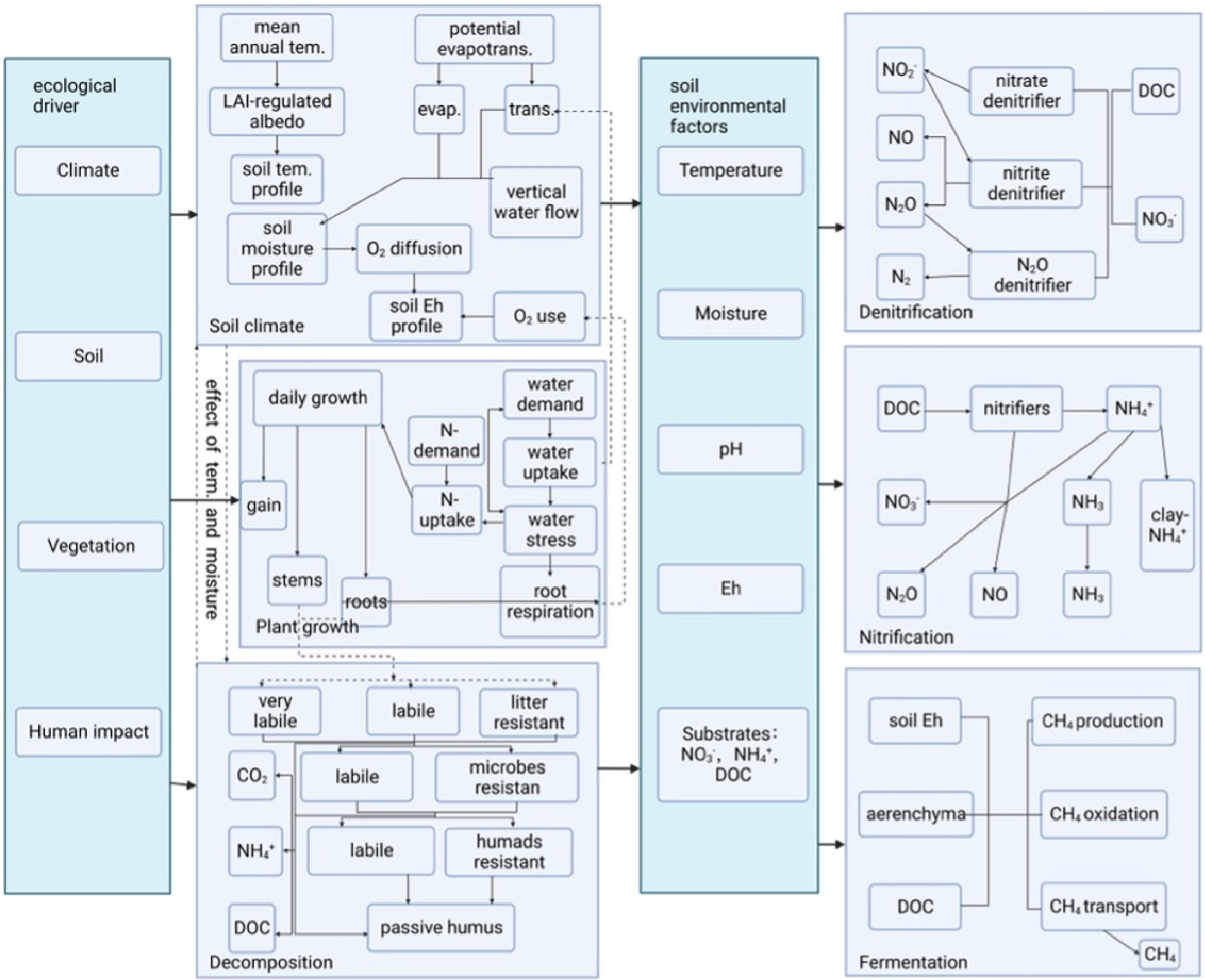
		more accurately estimate the growth and nitrogen uptake of spring wheat in Canadian agricultural ecosystems.
Y. Zhang et al. (2012)	NEST-DNDC	Develop an integrated approach to quantify CH_4 emissions under permafrost conditions and combine DNDC with NEST.
C. Li et al. (2012)	Manure-DNDC	Predict GHG and 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

		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

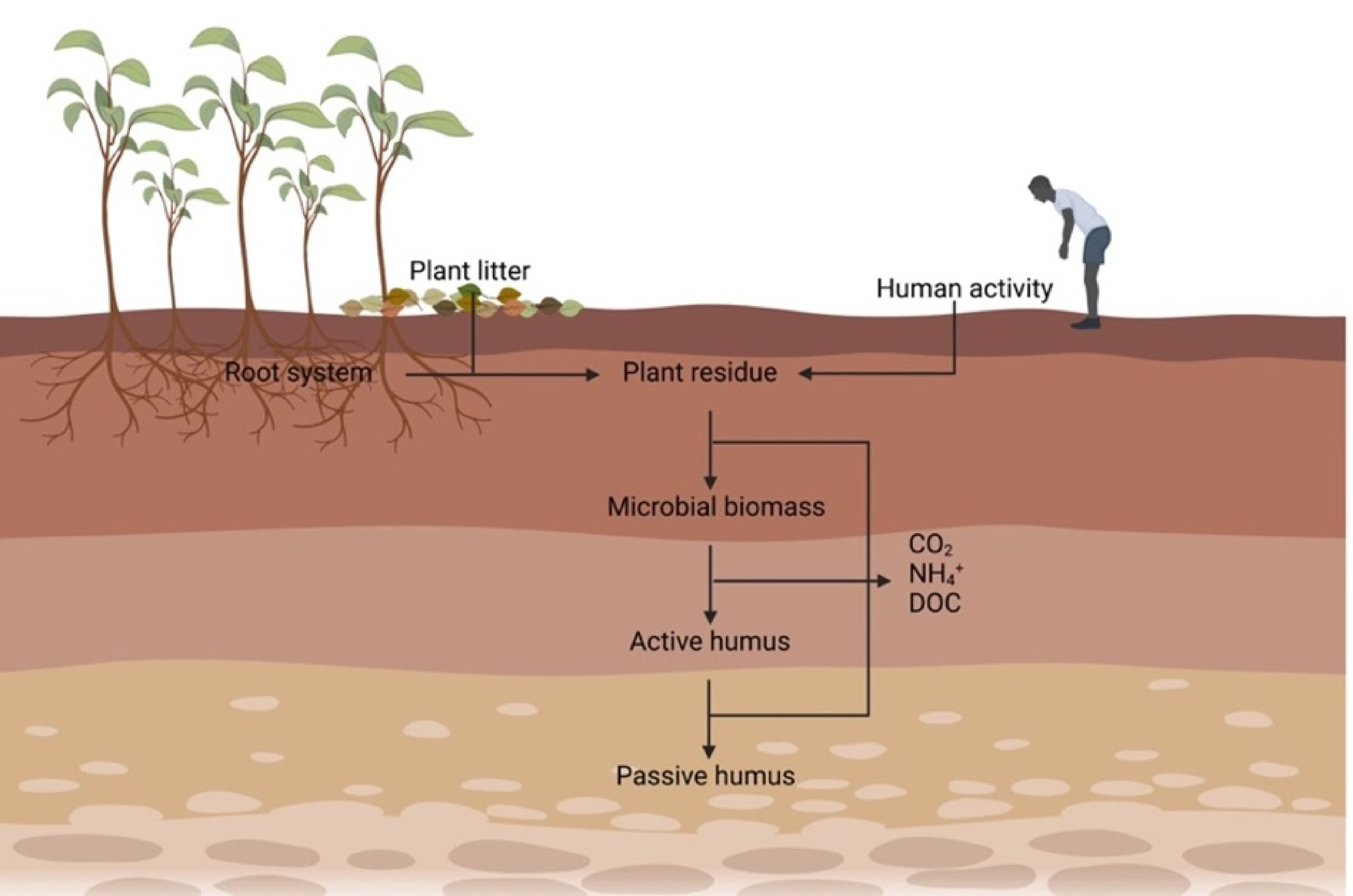
Publications	Ecosystem	Simulation parameter	Region
C. Li et al. (1994)	Cropland	N_2O	USA
C. Li et al. (1996)	Cropland	N_2O	USA
C. Li et al. (2001)	Cropland	N_2O	China
D. Giltrap et al. (2008)	Cropland	N_2O	New
Qiu et al. (2011)	Cropland	NO_3	China
Kesik et al. (2005)	Forest	N_2O, NO	Europe
C. Li, Cui, 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
DOC
nitrifiers
NH4+
NO3-
NH3
clay-NH4+
N2O
NO
NH3
Nitrification
soil Eh
aerenchyma
DOC
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