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# Interconnected Processes and Variables Influencing Soil-Atmosphere Carbon Exchange: A Survey

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## Abstract

This survey explores the intricate dynamics of soil respiration, moisture, temperature, and their collective influence on carbon exchange processes within terrestrial ecosystems. Soil respiration, driven by microbial activity, is pivotal in the global carbon cycle, with environmental factors like moisture and temperature significantly affecting these processes. The survey examines the mechanisms of soil respiration, emphasizing the role of soil moisture and temperature in microbial activity and carbon dynamics. Advanced modeling techniques, including ecosystem modeling and the integration of remote sensing data, are highlighted for their potential to enhance predictions of carbon fluxes under varying environmental conditions. The survey also delves into the feedback loops between soil respiration, moisture, temperature, and environmental factors, underscoring their impact on carbon cycling and ecosystem health. Challenges such as computational demands and data accuracy are addressed, alongside the implications for climate predictions and ecosystem management. The findings emphasize the necessity of high-resolution data and innovative modeling approaches to capture the complexities of these interactions, ultimately contributing to improved climate predictions and strategies for mitigating climate change impacts.

## 1 Introduction

### 1.1 Significance of Soil Respiration in the Carbon Cycle

Soil respiration is integral to the global carbon cycle, facilitating carbon dioxide (CO<sub>2</sub>) exchange between soil and atmosphere. This process is primarily driven by the metabolic activities of soil organisms, including bacteria, fungi, and plant roots, which decompose organic matter and release CO<sub>2</sub> as a byproduct [1]. Its significance is highlighted by the substantial contribution of soil respiration to the variability of the global terrestrial CO<sub>2</sub> sink, particularly as evidenced by Australia's role in global carbon dynamics [2].

The terrestrial biosphere mitigates climate change by sequestering approximately 25% of anthropogenic CO<sub>2</sub> emissions. However, variability in land carbon uptake introduces uncertainties in climate projections, necessitating a deeper understanding of soil carbon dynamics [3]. Soil organic carbon (SOC), formed through litter decomposition, is crucial for soil health and significantly contributes to the global carbon cycle.

Environmental factors, notably soil moisture and temperature, greatly influence soil respiration. For instance, precipitation variability can impact soil respiration rates in coastal wetlands, underscoring these ecosystems' role as significant carbon sinks due to their organic-rich soils [4]. Additionally, soil moisture is a critical variable within the climate system, affecting hydrological and energy cycles, especially in transitional zones. The observed temperature trends in western Europe, which exceed those predicted by General Circulation Models (GCMs), illustrate the complex interactions between temperature and soil carbon processes [5].

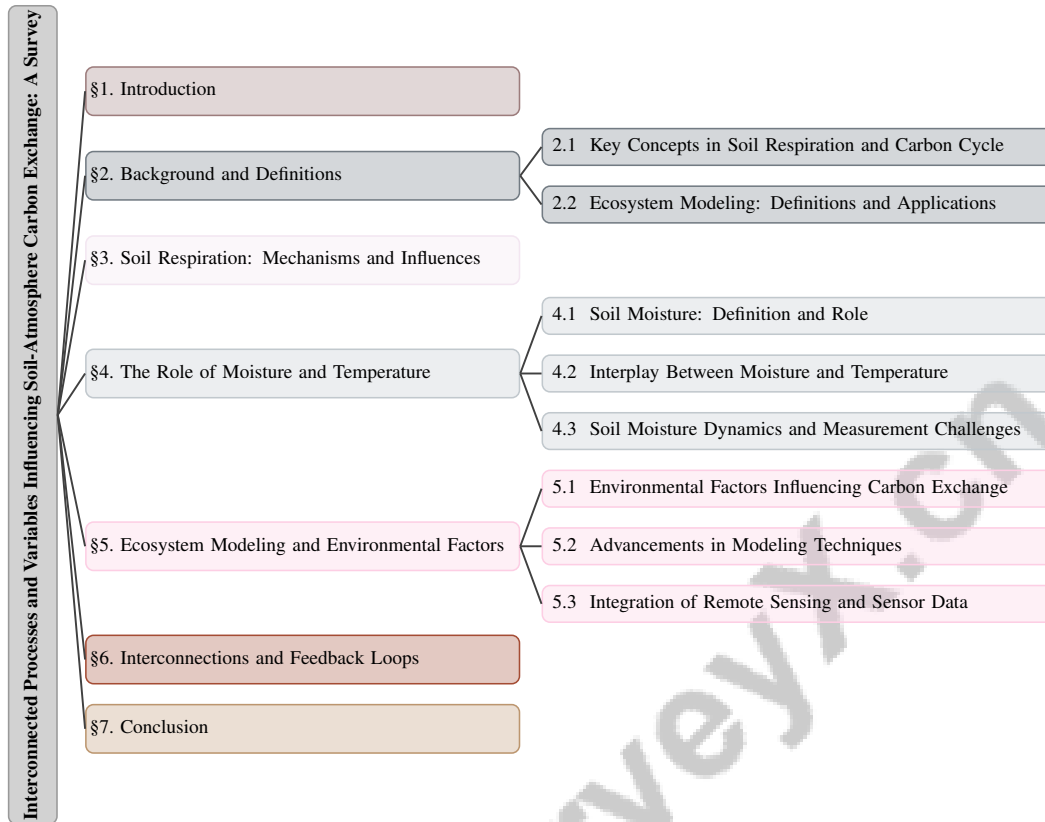


Figure 1: chapter structure

The interaction between soil moisture and atmospheric conditions is vital for understanding meteorological phenomena. These dynamics are influenced by the interplay of soil moisture and temperature, which are essential for enhancing weather and climate predictions. Moreover, soil moisture significantly drives European summer heat waves, further illustrating its impact on regional climate dynamics [6].

In the context of climate change, understanding how agricultural practices, such as nitrogen fertilizer applications, respond to abnormal weather conditions is critical for mitigating climate variability's impacts [7]. Additionally, the presence of nonbiodegradable microplastics in soil can alter microbial activity, including soil respiration, thereby influencing carbon exchange processes [8].

## 1.2 Structure of the Survey

This survey systematically explores the interconnected processes and variables influencing soil-atmosphere carbon exchange. Organized into several key sections, the paper begins with an introduction that establishes the significance of soil respiration within the carbon cycle, followed by a background section that provides foundational knowledge on concepts such as soil respiration, the carbon cycle, ecosystem modeling, and environmental factors, elucidating their interconnections and roles in carbon exchange processes.

Subsequently, the survey examines the mechanisms and influences of soil respiration, particularly focusing on biological and chemical processes. It analyzes how soil moisture and temperature affect microbial activity and  $\text{CO}_2$  release, supported by recent findings. A dedicated section further scrutinizes the roles of moisture and temperature on ecosystem processes and the broader carbon cycle while addressing the challenges of measuring soil moisture dynamics.

The survey then transitions to discussing ecosystem modeling and environmental factors, highlighting how models simulate interactions between soil and atmospheric carbon. This section explores the impacts of climate and land use on these models, alongside recent advancements in modeling techniques, including the integration of remote sensing and sensor data.

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Finally, the survey analyzes feedback loops between soil respiration, moisture, temperature, and environmental factors, discussing their influence on the carbon cycle and ecosystem health. The conclusion synthesizes key findings, addresses challenges and limitations, and discusses implications for climate predictions and ecosystem health management. This structured approach facilitates a thorough examination of the complex interactions that govern soil-atmosphere carbon exchange, particularly emphasizing the significant role of soil moisture variability in regulating terrestrial carbon uptake and its implications for climate modeling and predictions [9, 10, 11, 12]. The following sections are organized as shown in Figure 1.

## **2 Background and Definitions**

### **2.1 Key Concepts in Soil Respiration and Carbon Cycle**

Soil respiration is integral to the carbon cycle, facilitating CO<sub>2</sub> release from soil to the atmosphere, primarily driven by soil organisms like bacteria, fungi, and plant roots decomposing organic matter [13, 1]. This process is influenced by climatic conditions and litter types, affecting soil respiration rates and carbon exchange within ecosystems. Soil moisture, crucial for microbial activity and decomposition rates, significantly impacts the biogeochemical flux systems and carbon exchanges [14]. Variability in soil moisture can affect ecosystem productivity, particularly in semi-arid regions, where water stress reduces gross primary production and increases vegetation mortality. The interplay between soil moisture and temperature is vital for understanding soil respiration dynamics and the broader carbon cycle [15].

Root-zone soil moisture dynamics, governed by unsaturated flow and root water uptake, are essential for ecohydrological understanding [16]. Soil moisture variability demonstrates scale-invariance, linked to landslide frequency-size distributions [17]. Accurate soil moisture estimation, challenging in large agricultural fields, requires innovative sensor placement strategies [18]. The Cosmic-Ray Neutron Sensing (CRNS) technique effectively measures root-zone soil moisture over large areas, highlighting its importance in soil respiration and carbon dynamics [19].

Soil temperature also critically affects soil respiration. Global models often struggle to accurately predict soil respiration's temperature sensitivity due to complex interactions among soil properties, vegetation traits, and climate parameters [20]. Vegetation-climate interactions further complicate this relationship, influencing atmospheric processes and climate dynamics across scales [21]. Accurate soil thermal conductivity estimation is crucial for simulating soil temperature and heat fluxes in land surface models [22].

Environmental factors like temperature and humidity impact fungal decomposition, a key soil respiration component [23]. Ice and water films on soil particles significantly influence soil respiration and carbon exchange [24]. Land surface changes, which can decrease land relative humidity amid global warming, further complicate these interactions [25].

The nonlinear dynamics of these interactions, particularly regarding spatial heterogeneity and atmospheric conditions, complicate carbon cycle dynamics modeling and prediction. Understanding how these variables respond to environmental changes, such as deforestation and reforestation, is crucial for their influence on the water cycle and carbon dynamics [26]. Grasping these complex interconnections is essential for advancing carbon cycle knowledge and developing climate change mitigation strategies.

### **2.2 Ecosystem Modeling: Definitions and Applications**

Ecosystem modeling is crucial for simulating carbon dynamics within terrestrial ecosystems, offering insights into carbon exchange processes between soil and the atmosphere, with a focus on soil respiration's role in the global carbon cycle. These models integrate mechanistic and data-driven approaches to tackle challenges in predicting carbon fluxes across diverse environmental conditions [27]. Incorporating soil moisture dynamics is key to understanding carbon exchange processes. Accurate soil moisture data, often derived from satellite observations, is essential for effective modeling. Traditional disaggregation methods have limitations, necessitating high-resolution soil moisture data for improved model accuracy. The Seq2Seq-SM method exemplifies the innovative integration of satellite remote sensing data with advanced machine learning techniques, enhancing soil moisture predictions within ecosystem models. This approach addresses challenges related to

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coarse spatial resolution and data gaps in satellite observations while leveraging temporal correlations and auxiliary environmental information to produce high-resolution insights for precision agriculture and environmental management. Improved soil moisture estimates support critical agricultural objectives such as optimizing irrigation practices, increasing crop yields, and minimizing resource waste, thereby contributing to global sustainability goals [28, 29, 30, 31].

Advancements in sensor technology have enhanced ecosystem modeling by providing real-time soil moisture data. Comparative analyses of low-cost resistive and capacitive soil moisture sensors underscore the importance of precise calibration and responsiveness to varying water content [32]. These innovations facilitate integrating high-resolution data into models, enhancing their predictive capabilities.

Machine learning techniques, including graph neural networks, have significantly advanced ecosystem modeling. A novel graph neural network-based framework that learns temporal graph structures for soil moisture forecasting illustrates these approaches' potential in refining model accuracy [33]. The TimeGPT foundation model has been benchmarked against state-of-the-art models for forecasting soil moisture levels, showcasing the efficacy of advanced methods in improving predictions [34].

In mountainous regions, traditional models often struggle to capture interactions between environmental variables and carbon fluxes, particularly under changing climatic conditions [9]. The discrete mosaic approach addresses these limitations by explicitly representing spatial heterogeneity and capturing the non-unique relationships inherent in soil moisture dynamics [35]. Additionally, a proposed changepoint-based method for modeling soil moisture dynamics automates the identification of changes in soil moisture dynamics, leveraging advancements in sensor technology [36].

The inadequacy of previous methods in capturing the complexity of land surface processes necessitates a new approach using generalized polynomial chaos within a Bayesian framework [37]. This approach enhances ecosystem models' capacity to simulate complex hydrological and carbon dynamics.

In examining the intricate dynamics of soil respiration, it is essential to consider the various mechanisms and influences that govern this process. As depicted in Figure 2, the figure illustrates the hierarchical structure of soil respiration mechanisms and influences, categorizing the biological and chemical processes involved. It also emphasizes the impact of soil moisture on microbial activity and the effects of temperature variations. This visual representation not only highlights the interplay between environmental factors but also underscores the role of technological advancements in enhancing our understanding of soil respiration dynamics. By integrating these elements, we can better appreciate the complexity of soil ecosystems and the various factors that contribute to their functioning.

### **3 Soil Respiration: Mechanisms and Influences**

#### **3.1 Biological and Chemical Processes in Soil Respiration**

Soil respiration, a complex interplay of biological and chemical processes, facilitates the release of carbon dioxide (CO<sub>2</sub>) from soil to the atmosphere. Central to this process are the metabolic activities of soil microorganisms, including bacteria, fungi, and plant roots, which decompose organic matter, releasing CO<sub>2</sub> as a byproduct [7]. Environmental factors such as soil moisture and temperature significantly influence microbial activities and enzyme functions [16]. Soil moisture enhances substrate and oxygen diffusion, promoting microbial activity [30]. The interplay between moisture and temperature can create microbial activity hotspots, crucial for understanding soil respiration's spatial variability [38]. Nonbiodegradable microplastics can alter microbial activity, posing threats to soil health [7].

Chemical processes also impact soil respiration through interactions between soil minerals and organic compounds. Soil thermal conductivity, influenced by organic matter content and gravel, affects temperature dynamics and respiration rates [16]. Theoretical frameworks, such as dynamic transition theory, provide insights into atmospheric system stability and transitions, crucial for understanding soil respiration's broader implications on atmospheric processes [39]. Recent advancements in modeling, including physics-constrained deep learning frameworks, improve predictions of soil moisture dynamics by integrating sensor data and physical laws, enhancing our understanding of soil respiration and carbon flux dynamics [38, 25].

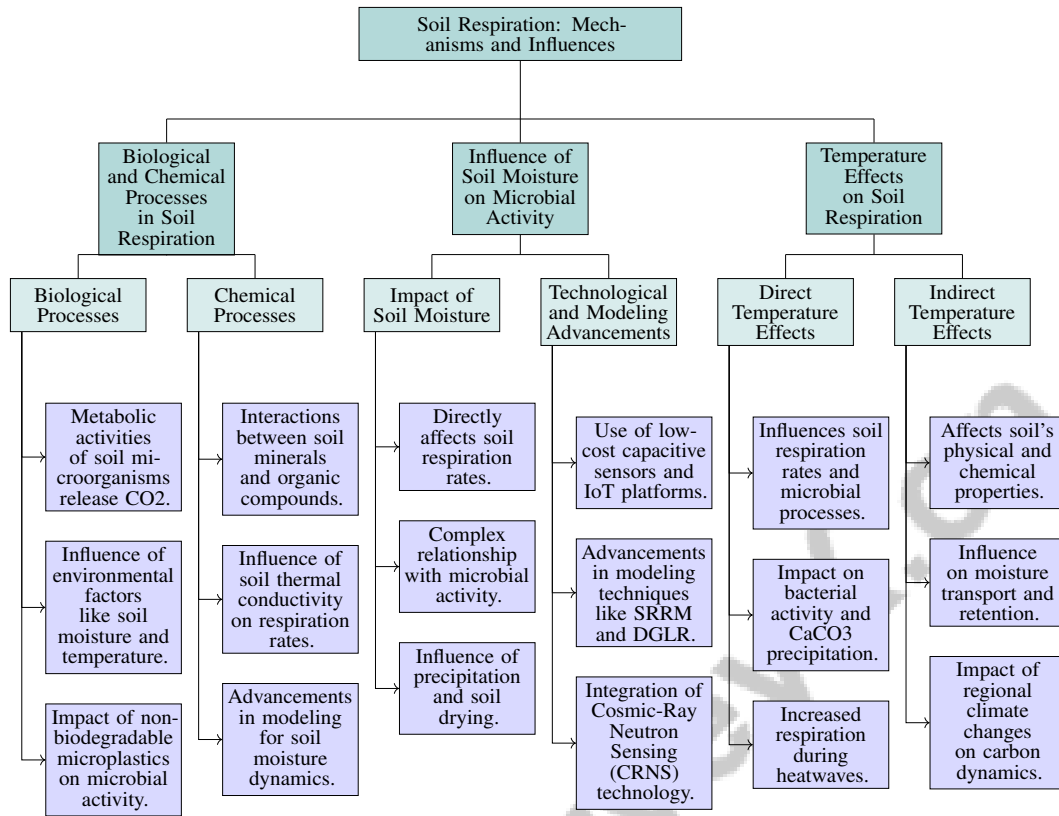


Figure 2: This figure illustrates the hierarchical structure of soil respiration mechanisms and influences, categorizing the biological and chemical processes, the impact of soil moisture on microbial activity, and the effects of temperature variations. It highlights the interplay between environmental factors and technological advancements in understanding soil respiration dynamics.

### 3.2 Influence of Soil Moisture on Microbial Activity

Soil moisture critically influences microbial activity, directly affecting soil respiration rates by modulating water availability essential for microbial metabolism. The sensitivity of microbial processes to moisture variations underscores the importance of accurate measurement and modeling of these dynamics. Recent advancements in sensor technology, such as low-cost capacitive sensors integrated with IoT platforms, enable real-time monitoring of soil parameters, including moisture content, vital for understanding microbial activity [40]. Precise calibration of these sensors is necessary for reliable data [32].

The relationship between soil moisture and microbial activity is complex, as moisture variations can significantly alter soil respiration. Increased moisture from precipitation can create anoxic conditions, inhibiting microbial activity and reducing respiration rates [4]. Conversely, soil drying, anticipated with climate change, can limit water availability, complicating soil respiration dynamics [41]. Advanced modeling techniques, such as the Self-Regularized Regressive Model (SRRM), enhance soil moisture estimation accuracy by clustering similar pixels and applying kernel regression, leading to more precise predictions of microbial activity and CO<sub>2</sub> release [42]. The Dynamic Graph Learning and Recurrent (DGLR) framework, integrating self-attention mechanisms with recurrent neural networks, further improves soil moisture predictions by capturing temporal dependencies [33].

The Soil Moisture Sensitivity Experiments (SMSE) method elucidates soil moisture's impact on temperature extremes, emphasizing the interconnectedness of these variables in influencing soil respiration [43]. Changepoint detection algorithms identify segments in soil moisture time series, offering sophisticated modeling of moisture dynamics and their influence on microbial processes [36]. The integration of Cosmic-Ray Neutron Sensing (CRNS) technology, with a correction function for different road types, enhances soil moisture estimates, elucidating moisture levels' influence

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on microbial activity and soil respiration [19]. Understanding soil moisture dynamics is crucial for predicting ecosystem responses to climate change and managing drought risks [44, 12, 20]. Integrating advanced sensor technologies and modeling approaches is essential for capturing these interactions, enhancing our understanding of carbon dynamics within terrestrial ecosystems.

### 3.3 Temperature Effects on Soil Respiration

Temperature significantly influences soil respiration rates and microbial processes, affecting organic matter decomposition and CO<sub>2</sub> release. Temperature variations impact bacterial activity and calcium carbonate (CaCO<sub>3</sub>) precipitation rates, highlighting microbial processes' sensitivity to temperature fluctuations [45]. During extreme weather events, such as heatwaves, soil respiration rates increase significantly, averaging 26% higher than non-heatwave conditions, due to heightened microbial metabolic activity [3].

Temperature variations also affect soil's physical and chemical properties, influencing moisture transport and retention. Modified boundary conditions in moisture transport models facilitate analyzing temperature-related changes in soil moisture dynamics, providing insights into the interactions between temperature, moisture, and microbial activity [46]. In Western Europe, observed temperature trends linked to atmospheric and oceanic circulation discrepancies contribute to regional warming patterns [5]. These trends illustrate the complex interplay between temperature and soil respiration processes, as regional climate changes significantly impact terrestrial ecosystems' carbon dynamics.

Temperature variations' multifaceted impact on soil respiration involves direct effects on microbial activity and indirect effects through changes in soil moisture and environmental conditions. A comprehensive understanding of interactions among soil properties, vegetation traits, and climate parameters is essential for accurately predicting soil respiration responses to ongoing climate change, particularly concerning extreme heat events and varying soil moisture levels. This knowledge is vital for developing effective strategies to mitigate these changes' impacts on the global carbon cycle, as current models often overlook the intricate controls exerted by soil development and ecosystem dynamics [12, 20, 3].

## 4 The Role of Moisture and Temperature

### 4.1 Soil Moisture: Definition and Role

Soil moisture, the volumetric water content in soil, is a fundamental factor in terrestrial ecosystem processes, significantly affecting soil respiration and carbon dynamics by regulating microbial activity involved in organic matter decomposition and CO<sub>2</sub> release [16, 2]. Changes in soil moisture, particularly during rewetting events, can lead to significant shifts in carbon dynamics.

Accurate soil moisture monitoring and modeling are essential due to its critical impact on ecosystem processes. The CRNS Rover, which estimates soil moisture through cosmic-ray neutron counts, offers a non-invasive assessment method that enhances our understanding of soil moisture's role in carbon dynamics [19]. However, deploying numerous sensors for high spatial resolution remains impractical due to cost constraints [38].

Disaggregating coarse satellite soil moisture data to finer resolutions, such as 1 km, is crucial for hydrological and agricultural models, offering a more precise understanding of soil moisture's role in carbon dynamics [42]. This precision is particularly important in agriculture, where soil moisture directly impacts management practices and productivity, as evidenced by datasets that incorporate soil water potential and environmental factors [34].

Soil moisture variability affects ecosystem processes like organic matter decomposition rates and landslide susceptibility. Monitoring these dynamics can improve hazard assessments and our understanding of their impact on carbon dynamics [17]. However, analyzing its influence on climate variables, such as heat events, is often limited by data availability, complicating efforts to draw robust conclusions about their frequency and intensity [6].

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## 4.2 Interplay Between Moisture and Temperature

The interactions between soil moisture and temperature are pivotal in shaping soil respiration dynamics and broader ecosystem processes. These factors jointly influence microbial activity, organic matter decomposition, and CO<sub>2</sub> release. Wavelet cross-correlation analysis has revealed multiscale interactions between soil moisture and temperature, elucidating their combined effects on soil respiration [15]. Understanding these interactions is crucial for grasping the temporal variability of soil respiration rates and their implications for carbon cycling.

The coupling between soil moisture and temperature also modulates temperature extremes, significantly impacting atmospheric conditions [43]. This interaction can alter the energy balance within ecosystems, affecting the frequency and intensity of temperature extremes, which are vital for predicting climate variability.

Vegetation feedbacks further complicate these interactions by influencing energy, water, and carbon cycles, interacting with atmospheric processes to modulate climate dynamics [21]. Vegetation can enhance soil moisture retention and temperature regulation, thereby influencing soil respiration rates.

Understanding soil water dynamics, including its variability and memory, is essential for grasping the interactions between soil moisture and temperature and their implications for climate change [47]. Recent advancements in modeling techniques, such as the domain-inspired temporal graph convolution neural network (TGCN), have improved predictions of soil moisture dynamics, underscoring the importance of integrating soil moisture data into models to better understand its interactions with temperature [27]. These models are crucial for forecasting soil respiration responses to environmental changes and developing strategies to mitigate climate change impacts.

## 4.3 Soil Moisture Dynamics and Measurement Challenges

Understanding soil moisture dynamics is vital for accurately modeling terrestrial ecosystem processes and predicting carbon exchange rates. Soil moisture is influenced by precipitation, evapotranspiration, and subsurface water flow, creating complex patterns challenging to capture. The inherent spatial and temporal variability necessitates advanced measurement techniques for precise data collection [48].

Traditional soil moisture measurement techniques often struggle with spatial resolution and accuracy limitations. Recent advancements propose machine learning methods to enhance prediction accuracy, offering efficient alternatives to address these challenges [28]. Additionally, Rydberg atomic sensors for soil moisture detection streamline remote sensing by dynamically tuning across a broad spectrum and utilizing existing satellite signals, thereby improving remote sensing efficiency [49].

The deployment of wireless sensor networks (WSNs) for in situ soil moisture monitoring has significantly advanced real-time data capture, yet these systems face standardization and comparability challenges across different platforms [50]. Developing benchmarks for evaluating WSNs aims to address these issues, enhancing soil moisture monitoring technologies. Despite advancements, traditional land surface models (LSMs) still introduce biases in soil moisture predictions, leading to significant errors in weather and climate modeling [51].

Satellite-derived soil moisture data, while useful, often suffer from coarse spatial resolution and information gaps, limiting their effectiveness for detailed ecological studies [31]. The Boosted Regression Trees (BRT) method offers accurate downscaling with significantly less in situ training data compared to traditional methods, making it suitable for data-sparse regions [30]. However, challenges persist, including the lack of rigorous comparative assessments of downscaling techniques and variability in performance due to differing weather and climate conditions [10].

A global, long-term soil moisture dataset generated from in-situ measurements using machine learning serves as a valuable resource for hydrological, meteorological, and ecological analyses [29]. However, reliance on available observational data may not fully capture the complexities of soil moisture dynamics across regions [47]. Innovative upscaling approaches that integrate spatiotemporal fusion with machine learning have been proposed to extrapolate soil moisture measurements to scales compatible with climatic model grids and satellite retrievals [14].

The changepoint-based method offers significant advantages, including reduced manual effort and the ability to handle large datasets, which are crucial for understanding soil moisture dynamics [36]. These advancements underscore ongoing challenges related to spatial resolution, data gaps, and model

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biases, highlighting the need for continued innovation in this field. Addressing these challenges is critical for enhancing our understanding of soil moisture dynamics and their implications for carbon cycling and ecosystem health.

## 5 Ecosystem Modeling and Environmental Factors

### 5.1 Environmental Factors Influencing Carbon Exchange

Environmental factors are pivotal in regulating carbon exchange between soil and atmosphere, impacting the terrestrial carbon cycle and ecosystem productivity. Key elements include soil moisture, which mitigates drought stress and enhances vegetation growth; temperature, influencing metabolic rates and carbon uptake; vegetation dynamics, encompassing community changes and physiological responses; and hydrological interactions, involving soil moisture, atmospheric conditions, and water availability. These factors collectively determine terrestrial ecosystems' carbon sequestration capacity and influence climate projections [26, 44, 12].

Soil moisture is a fundamental determinant of carbon exchange, affecting microbial activity and organic matter decomposition. Automated soil respiration measurements reveal significant correlations between soil moisture levels and respiration rates, emphasizing its role in carbon dynamics [36]. Accurate integration of soil moisture data into ecosystem models is crucial for optimizing agricultural practices and improving carbon exchange predictions. However, challenges persist in measuring soil moisture accurately due to terrain influences and sensor calibration needs [19]. Sparse sensor data and the need for predictions at multiple depths complicate this task, as existing methods often provide only surface-level predictions [37].

Temperature significantly influences carbon exchange processes, with soil temperature and moisture interactions being critical for understanding carbon dynamics. Soil moisture variations affect ecosystem productivity and carbon uptake, as moisture is the dominant factor driving drought stress across over 70% of vegetated land. Increased soil moisture variability can enhance fungal biodiversity and decomposition rates, while extreme heat events elevate soil respiration, highlighting the complex interplay of these factors in shaping carbon cycling [52, 12, 20, 44, 3]. During extreme weather events, such as heatwaves, soil respiration rates can exceed average values, underscoring carbon exchange sensitivity to temperature fluctuations, further complicated by vegetation and hydrological interactions affecting soil moisture retention and energy balance.

Vegetation dynamics, particularly the interactions between vegetation and hydrology, are crucial in regulating carbon exchange and influencing climate systems. Vegetation responds to long-term climate conditions while actively shaping the Earth's climate by modulating energy, water, and biogeochemical cycles. Changes in vegetation cover, such as deforestation, can disrupt local moisture regimes, leading to fluctuations in the water cycle and increasing the likelihood of extreme weather events like droughts and floods. Understanding these feedback mechanisms is essential for accurately modeling climate processes and developing effective climate change mitigation strategies [21, 53]. Tree root-water uptake significantly affects subsurface water flow, influencing soil moisture availability and carbon fluxes. The presence of vegetation complicates accurate soil moisture measurement due to additional gamma-ray signal attenuation, making it crucial to optimize soil and vegetation parameters in land surface models for accurate simulations of terrestrial water, energy, and carbon cycles.

Hydrological interactions, including soil hydrology and variations in hysteresis and bulk density, significantly impact carbon exchange processes. The limited representativeness and uneven distribution of point-scale measurements can introduce biases in validating model simulations and satellite retrievals, highlighting challenges in accurately capturing hydrological dynamics. New approaches are necessary to address difficulties encountered in existing model boundary conditions, complicating analysis and application. The global disparity in hydrological observation stations hampers the training and validation of hydrological models in ungauged regions, affecting the reliability of both process-based and data-driven models used for predicting essential water cycle variables like runoff, evapotranspiration, and soil moisture. Strategies to enhance model extrapolability, including leave-one-out cross-validation and machine learning techniques like transfer learning, are essential for improving model performance in data-sparse environments, ensuring effective water resource management and ecological protection [54, 55, 56, 57].



Moisture transport from the ocean to land is vital for regulating land relative humidity, a key environmental factor influencing carbon exchange. Changes in vegetation cover can disrupt moisture transport dynamics, potentially leading to abrupt shifts in local humidity levels. The declining land relative humidity associated with global warming is linked to increased land-ocean temperature contrasts, exacerbating soil moisture variability's effects on terrestrial carbon uptake. Understanding these interactions is crucial for predicting climate impacts and developing effective ecosystem conservation strategies [26, 25, 53, 12]. Future research should enhance datasets for extreme events, explore the impacts of other climatic drivers, and employ advanced modeling techniques to improve predictions of heatwave occurrences. The proposed LRBF meshless method exemplifies how ecosystem models simulate interactions between soil moisture and atmospheric carbon exchange.

Environmental factors such as soil moisture, temperature, vegetation dynamics, and hydrological interactions are integral to understanding carbon exchange processes. The ongoing development of sensor technologies, advanced data integration techniques, and sophisticated modeling approaches is crucial for effectively monitoring and understanding the intricate dynamics of the carbon cycle in response to environmental changes. Wireless sensor networks have enabled unprecedented precision in soil moisture and temperature measurements, vital for assessing soil conditions' impacts on carbon uptake. Additionally, transformer-based data fusion methods have shown significant improvements in predicting soil-related variables, enhancing our ability to model carbon fluxes accurately. These advancements contribute to refining climate projections by elucidating the complex interactions between soil moisture variability and terrestrial carbon dynamics [58, 9, 12, 54, 11].

## 5.2 Advancements in Modeling Techniques

Method Name	Technological Integration	Predictive Capabilities	Environmental Insights
BRT[30]	Bagged Regression Trees	Accurate Downscaling Soil	Temporal Correlations Insights
P-DAL[38]	Deep Learning	Soil Moisture Prediction	Environmental Patterns
XKGC[59]	Gaussian Processes	Soil Moisture	Climate-vegetation Dynamics
SROM[60]	-	Accurate Predictions	Heat Moisture Transfer
PC[61]	-	-	Complex Systems Understanding
LFM[62]	Hybrid Learning Schemes	Accurate And Informative	Complex Environmental Patterns
ML-MCMC-	Machine Learning	Soil Moisture	Carbon Fluxes
LSM[57]	-	-	-
BA[63]	Bayesian Modeling Integration	Improved Predictive Performance	Complex Environmental Patterns

Table 1: This table provides a comprehensive comparison of various modeling techniques used in ecosystem modeling, highlighting their technological integration, predictive capabilities, and environmental insights. The methods include approaches such as Bagged Regression Trees, Deep Learning, and Gaussian Processes, each contributing uniquely to advancements in soil moisture prediction, climate-vegetation dynamics, and heat moisture transfer. The table underscores the importance of integrating machine learning and hybrid learning schemes for improved predictive performance and understanding of complex environmental patterns.

Recent advancements in ecosystem modeling have significantly enhanced our understanding of carbon dynamics through the integration of cutting-edge technologies and methodologies. Agricultural remote sensing has been notably influenced by machine learning, deep learning, and advanced statistical methods, particularly transformer-based data fusion techniques. These approaches have markedly improved model accuracy and predictive capabilities, achieving prediction performances between 92% and 97% in soil analysis. Deep learning regression networks have effectively predicted soil moisture by addressing complex structural characteristics and meteorological factors. By leveraging big data fitting capabilities and analyzing temporal relationships among predictive variables, these models have improved generalization and accuracy, providing valuable insights for optimizing water resource management and enhancing sustainable agricultural practices [58, 64].

Integrating machine learning with process-based models has substantially improved soil moisture state predictions. Combining deep learning methodologies with traditional interpolation methods, as demonstrated by recent downscaling techniques, provides accurate soil moisture predictions across entire areas rather than just at sensor locations [30]. These advancements in downscaling techniques have improved soil moisture estimation accuracy and spatial resolution, highlighting the potential of combining parametric and non-parametric approaches to enhance model performance [10].

Innovations in data assimilation methods, such as the Dynamic Graph Learning and Recurrent (DGLR) framework, have demonstrated superior performance in soil moisture prediction, especially

in the presence of missing data. This framework effectively integrates incomplete datasets, enhancing model prediction reliability. The P-DAL framework improves soil moisture estimation accuracy by integrating physical principles with an innovative active learning approach for optimal sensor placement [38], underscoring the importance of sensor placement in enhancing data quality and model precision.

Logistic principal component analysis combined with neural networks has been proposed to analyze and explain heatwave occurrences, showcasing these advanced methods' capability to capture complex environmental patterns [59]. Additionally, the proposed nonlinear Granger causal methodology generalizes kernel Granger causality by explicitly considering the cross-relations of variables in Hilbert spaces, offering new insights into climate variables and carbon dynamics interactions.

The spectral reduced-order method simplifies heat and moisture transfer modeling by leveraging spectral expansions, allowing for a more efficient representation of solutions [60]. The flexibility and extensibility of PyCascades enable researchers to model various tipping elements and their interactions, providing a robust framework for understanding nonlinear dynamics within ecosystems [61].

Recent modeling advancements have greatly enhanced our understanding of carbon dynamics, particularly in high-altitude regions where climate change rapidly impacts carbon cycles. Systematic statistical analyses comparing three empirical modeling approaches have identified key environmental variables—such as solar irradiance, soil moisture, and temperature—that significantly influence carbon fluxes in Alpine tundra and grasslands. These refined models demonstrate high explanatory power, accounting for 83% to 94% of variability in gross primary production and ecosystem respiration. Insights into soil moisture's role as a limiting factor for land carbon uptake reveal its critical impact on long-term carbon storage and ecosystem health, underscoring the importance of these modeling advancements for improving climate predictions and understanding carbon dynamics across various landscapes [9, 12]. The continuous integration of innovative technologies drives progress in this field, offering promising avenues for future research and application in ecosystem modeling. Table 1 presents a detailed comparison of recent advancements in modeling techniques, illustrating their integration of advanced technologies and contributions to enhancing predictive accuracy and environmental insights in ecosystem studies.

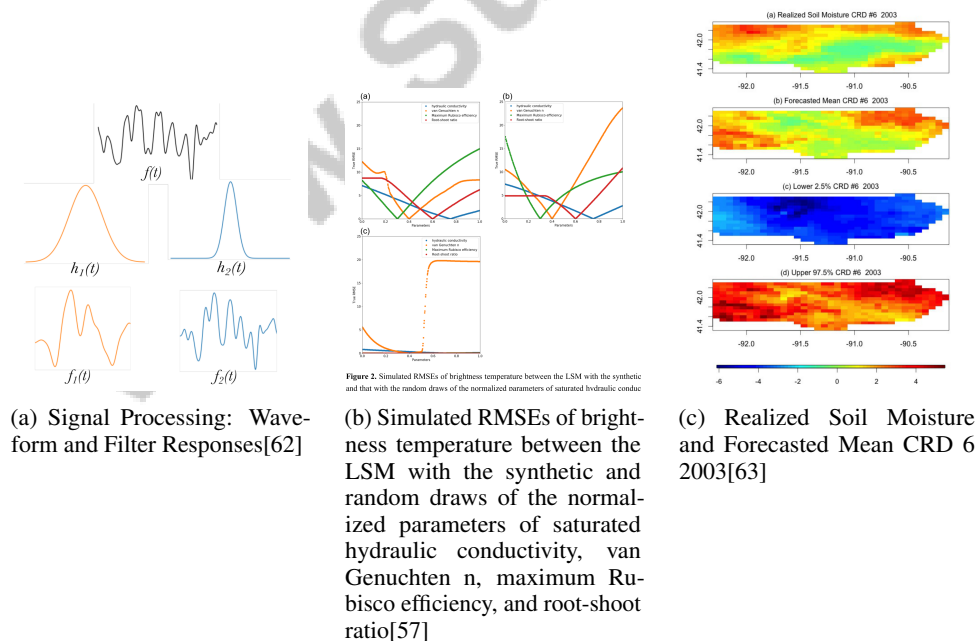


Figure 3: Examples of Advancements in Modeling Techniques

As shown in Figure 3, understanding and predicting environmental factors in ecosystem modeling is pivotal for advancing ecological systems' knowledge and management. The figure showcases advancements in modeling techniques through three distinct examples illustrating the integration

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of signal processing and environmental parameter simulations. The first example, "Signal Processing: Waveform and Filter Responses," demonstrates signal transformation through various filters, highlighting data interpretation refinement potential in ecological studies. The second example, "Simulated RMSEs of brightness temperature," delves into Land Surface Models' precision by comparing simulated errors using different parameter sets, such as saturated hydraulic conductivity and Rubisco efficiency, thereby enhancing environmental predictions' accuracy. Lastly, the "Realized Soil Moisture and Forecasted Mean CRD 6 2003" example visualizes soil moisture dynamics, offering detailed insights into moisture levels over time and space. Together, these examples underscore ongoing advancements in modeling techniques crucial for deciphering environmental factors' complex interplay within ecosystems [62, 57, 63].

### 5.3 Integration of Remote Sensing and Sensor Data

Integrating remote sensing technologies and sensor data is crucial for enhancing ecosystem models by providing high-resolution, real-time data essential for understanding carbon dynamics. Remote sensing technologies, such as Rydberg atomic sensors, have significantly improved soil moisture data retrieval by leveraging existing satellite signals, enhancing ecosystem models' accuracy regarding soil moisture, a critical factor in carbon exchange processes [49].

Using remote sensing data alongside slope stability analysis has improved modeling landslide frequency-size distributions, demonstrating the utility of integrating remote sensing technologies in environmental modeling [17]. This integration allows for a comprehensive understanding of soil moisture's spatial variability and its impact on ecosystem processes.

Incorporating remote sensing data into ecosystem models facilitates evaluating predictive errors and uncertainty estimates, as demonstrated by the Monte Carlo Dropout with Aleatoric Uncertainty (MCD-AU) method. This method effectively captures predictive errors and provides reliable uncertainty estimates, confirming its suitability for hydrologic datasets [51]. Accurately assessing uncertainties is crucial for improving ecosystem model predictions' reliability.

Future research should apply these models to additional regions, integrate remote sensing data more extensively, and explore the impact of different meteorological inputs on prediction accuracy. By expanding remote sensing technologies and sensor data applications, researchers can enhance ecosystem models' predictive capabilities, leading to a deeper understanding of carbon dynamics and more effective natural resource management strategies [64].

The integration of remote sensing technologies and sensor data is essential for advancing ecosystem modeling. These technologies enhance our understanding of soil moisture dynamics and other critical environmental factors, improving carbon exchange simulations' accuracy. By integrating insights from global land-atmosphere models and deep learning algorithms, researchers can better predict soil moisture trends and their impact on terrestrial carbon uptake. This knowledge aids in refining climate models and informs effective strategies for mitigating climate change impacts, such as optimizing water resource management and enhancing agricultural resilience [10, 64, 36, 12].

## 6 Interconnections and Feedback Loops

### 6.1 Feedback Mechanisms and Interactions

Feedback mechanisms among soil respiration, moisture, temperature, and environmental factors are crucial for understanding carbon cycle dynamics and ecosystem health. Complex feedback loops characterize the interactions between vegetation and climate, where vegetation not only responds to climatic conditions but also regulates energy, water, and biogeochemical cycles. These interactions influence atmospheric dynamics, impacting local microclimates and global circulation patterns, which affect precipitation, temperature trends, and extreme weather events like droughts and heatwaves. Understanding these interactions, particularly the roles of soil moisture and vapor pressure deficit, is vital for predicting ecosystem resilience to climate variability and enhancing climate models [65, 21, 44, 66]. Soil respiration, a critical component of the carbon cycle, is highly sensitive to temperature variations influenced by soil properties and atmospheric conditions. Current global models often underestimate future soil respiration rates due to insufficient representation of soil development factors, highlighting the need for improved parameterization in ecosystem models.

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The interplay between soil moisture and temperature is particularly significant in determining soil respiration rates. Feedback mechanisms involving soil moisture and temperature extremes can impact the frequency, duration, and intensity of extreme temperature events. Discrepancies between observed and modeled temperature trends, due to misrepresentations of atmospheric circulation and oceanic currents, emphasize the necessity of accurately capturing these interactions [17]. The application of Cosmic-Ray Neutron Sensing (CRNS) technology enhances our understanding of feedback mechanisms between soil moisture and environmental factors [19].

Vegetation dynamics significantly influence climate through various mechanisms, contributing to a deeper understanding of land-atmosphere interactions. The Yasso07 model illustrates how vegetation and litter quality affect soil respiration, underscoring the importance of incorporating vegetation dynamics into ecosystem models to accurately capture feedback mechanisms. Interspecies interactions among fungal species further complicate these mechanisms, impacting soil respiration and broader ecosystem processes [36].

Theoretical perspectives on the coupling strength between surface and subsurface soil moisture provide insights into feedback loops within ecosystems. The timing of soil respiration in response to rainfall is crucial for understanding CO<sub>2</sub> flux variability, emphasizing the significance of feedback loops between soil respiration and moisture dynamics. Additionally, spatial heterogeneity effects on water balance components are better predicted through approaches that accurately represent these complexities [37].

Advanced modeling techniques, including Bayesian variable selection methods combined with generalized polynomial chaos expansions, enhance statistical efficiency in capturing these interactions, facilitating stable computations with large datasets. Feedback mechanisms between soil moisture and agricultural management are critical for developing improved management practices and enhancing ecosystem health. The effectiveness of methods like the SRRM, which clusters similar conditions to tailor regression models, provides insights into feedback mechanisms influencing carbon dynamics [37].

Integrating advanced modeling techniques, high-resolution datasets, and data-driven approaches is essential for effectively capturing the intricate interactions within ecosystems, thereby enhancing our understanding of their contributions to ecosystem health and carbon exchange processes. This multidisciplinary approach combines process-based models simulating physical mechanisms governing hydrological and ecological dynamics with data-driven methods leveraging extensive datasets and machine learning algorithms. By employing hybrid models that incorporate domain knowledge and statistical learning, researchers can analyze complex phenomena such as carbon fluxes in high-altitude ecosystems and tree interactions under varying environmental conditions. Such comprehensive modeling strategies improve predictive accuracy and facilitate informed decision-making in water resource management, agricultural practices, and climate change mitigation efforts [58, 9, 54, 62, 67].

## 6.2 Feedback Loops and Climate Extremes

Feedback loops significantly shape climate extremes and impact carbon dynamics. These loops, involving interactions among soil moisture, temperature, and atmospheric processes, can amplify or mitigate the effects of extreme weather events on carbon exchange processes. For instance, the correlation between soil moisture and rainfall patterns exemplifies feedback loops where variations in soil moisture can influence precipitation dynamics, thereby affecting the hydrological cycle and carbon fluxes [68].

The complexity of feedback mechanisms is further underscored by distinct memory timescales for surface and subsurface soil moisture, influencing hydrological processes during extreme weather events. These memory effects can modulate the persistence of soil moisture anomalies, impacting the frequency and intensity of climate extremes such as droughts and heatwaves [47]. The variability in these processes highlights the need for advanced modeling techniques that capture the nonlinear interactions and dependencies inherent in climate systems.

The Weather Research and Forecasting (WRF) model has been instrumental in understanding surface evapotranspiration (SFCEVP) dynamics, particularly in the Iberian Peninsula. Insights from the model regarding projected reductions in SFCEVP have significant implications for climate change

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adaptation strategies, as they reveal how feedback loops can influence regional climate patterns and carbon dynamics [69].

Machine learning approaches have also advanced our understanding of heatwave factors by analyzing nonlinear relationships and interactions. These methods provide a comprehensive view of the feedback loops driving extreme temperature events, elucidating the complex interplay between soil moisture, temperature, and atmospheric conditions [70]. However, the reliability of downscaled products depends on the quality of coarse passive microwave data and performance variability across different climatic conditions, posing challenges for accurately modeling feedback loops in diverse environments [10].

### 6.3 Hydrological and Ecological Feedbacks

Hydrological and ecological feedbacks are critical in shaping ecosystem health and influencing carbon exchange processes. The intricate interactions among soil moisture, vegetation dynamics, and atmospheric conditions significantly affect carbon fluxes and ecosystem resilience. Soil moisture acts as the primary driver of dryness stress on vegetation, impacting growth and carbon uptake, particularly in semi-arid regions. Vegetation, in turn, regulates the terrestrial water cycle through processes such as transpiration, affecting atmospheric moisture convergence and precipitation patterns. These complex feedback mechanisms underscore the crucial role of vegetation in modulating climate at various scales, influencing ecosystem responses to environmental changes and the stability of carbon storage in terrestrial landscapes. Understanding these interactions is vital for improving climate models and effectively managing drought risks [26, 21, 44].

Hydrological feedbacks driven by soil moisture dynamics influence water availability and distribution within ecosystems. The integration of advanced modeling techniques, such as those presented by Demontoux et al., enhances the accuracy of soil moisture estimations by accounting for multiple factors [71]. Accurate soil moisture data is essential for understanding hydrological processes and their feedbacks on ecosystem health.

Ecological feedbacks involving vegetation dynamics play a vital role in regulating carbon exchange processes. Vegetation influences soil moisture retention and temperature regulation, affecting microbial activity and organic matter decomposition. The interactions between vegetation and hydrology create complex feedback loops that can either stabilize or destabilize ecosystem functions, depending on various environmental conditions and management practices. For example, vegetation affects the terrestrial water cycle through transpiration, which can enhance moisture import in certain climates or reduce moisture availability in drier conditions. Regions identified as coupling hotspots exhibit varying responses to changes in vegetation, emphasizing the critical role of soil moisture in these interactions. Understanding these nuanced relationships is crucial for predicting ecosystem responses to environmental changes and developing effective management strategies [26, 65, 21].

The interplay between hydrological and ecological feedbacks is further complicated by climate variability, which can significantly alter precipitation patterns and temperature regimes. This dynamic relationship is influenced by vegetation's role in regulating energy, water, and biogeochemical cycles across terrestrial landscapes. For instance, vegetation modifies surface roughness and influences atmospheric moisture through transpiration and interception, which can either enhance or diminish atmospheric moisture convergence based on prevailing humidity conditions. Consequently, changes in vegetation cover, such as deforestation or re-greening, can lead to unpredictable shifts in local and regional water cycles, impacting ecosystem health and human well-being. Understanding these interactions is essential for accurately predicting climate impacts and developing effective land management strategies [26, 21]. These changes affect soil moisture levels and vegetation growth, leading to shifts in carbon dynamics and potential alterations in ecosystem health. The resilience of ecosystems to adapt to these changes relies on the robustness of their feedback mechanisms and their capacity to maintain functional stability under varying conditions.

## 7 Conclusion

### 7.1 Challenges and Limitations

Understanding soil-atmosphere carbon exchange presents notable challenges, primarily due to the computational intensity of advanced modeling techniques such as Gaussian process modeling, which

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limits their practical application in forecasting. These complexities are exacerbated by difficulties in modeling atmospheric circulations and humidity, which require sophisticated analytical solutions. Additionally, the accuracy of soil moisture retrieval is constrained by the quality of sensor data and the ability to manage soil moisture variability. Techniques like downscaling often falter in areas with significant data gaps or diverse land cover, necessitating improvements in multi-sensor data integration for enhanced accuracy.

Moreover, models based on theoretical assumptions, like the Kirchhoff transformation, often fail to align with real-world conditions, limiting their effectiveness in capturing carbon flux dynamics. Empirical data reliance further complicates insights into rapidly changing environments, and methodologies may not fully encapsulate the complexities of land surface processes, especially with non-linear parameter relationships. Furthermore, the generalizability of findings is limited, as studies often focus on specific locations, making it challenging to apply results broadly across ecosystems. Current modeling approaches, such as the box model, are also limited in their ability to account for all factors affecting land humidity, complicating simulations of soil-atmosphere interactions.

Addressing these challenges requires advancements in sensor technology, data integration, and modeling techniques to enhance the robustness of soil-atmosphere carbon exchange research. Future research should focus on developing cohesive frameworks for soil moisture retrieval and refining models to better represent these complex interactions, ultimately improving our understanding of carbon dynamics and ecosystem health.

## **7.2 Implications for Climate Predictions and Ecosystem Health**

The survey highlights significant implications for climate predictions and ecosystem health management, particularly concerning soil moisture and temperature dynamics. Advanced modeling methods, such as the LRBF meshless method, hold potential for accurately predicting soil moisture dynamics, which is crucial for improving climate forecasts and managing agricultural ecosystems. Incorporating soil moisture feedback mechanisms into forecasting models can enhance climate prediction reliability and clarify the influence of these variables on carbon exchange and ecosystem responses.

Adaptive behaviors in fertilizer application underscore the importance of considering climate variability in agricultural practices, promoting sustainable carbon management and ecosystem resilience. Vegetation dynamics play a pivotal role in climate models, acting as both mitigators and contributors to climate extremes. Understanding vegetation feedbacks is vital for developing effective ecosystem health management strategies, especially as climate change necessitates adaptation to evolving environmental conditions.

Implications for ecosystem health management include soil stabilization and environmental remediation. Insights from temperature-dependent microbial processes inform sustainable management practices, while benchmarks for global soil moisture variability improve our understanding of its impact on climate and hydrological processes. The potential exacerbation of carbon losses from ecosystems, such as coastal wetlands, due to climate change highlights the need to incorporate moisture dynamics into geophysical fluid dynamics to advance climate understanding and mitigate adverse ecosystem impacts. Future research should aim to relax assumptions in current models and explore complex scenarios to refine climate predictions. Additionally, the long-term impacts of microplastics on soil health and their interactions with other pollutants require further investigation to understand their ecological consequences fully.

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