Coupling Models for Forest Fire Behavior Simulation: State of the Art and Future Perspective

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Resumen Wildfires are complex phenomena that involve dynamic interactions between fire, the atmosphere, vegetation, and other environmental components. To capture this complexity and achieve more realistic simulations of fire spread and its feedbacks, the scientific community has developed coupled models. These systems integrate a fire behavior model with other models, such as meteorological or ecological models. Modeling has evolved from decoupled approaches with static inputs to coupled systems that capture dynamic feedback mechanisms. There are two main categories: quasi-physical coupled models that incorporate fire-atmosphere physics through semi-empirical relationships for heat release and spread rates, and physics-based models that represent fire behavior at a more sophisticated level, resolving combustion processes with high resolution. The key advantages of coupled models lie in their ability to simulate extreme fire behaviors, such as eddies and towering convection columns, and to predict spotting. However, their most significant limitation is their substantial computational demands, which often preclude their real-time use for operational forecasts. The future of coupled modeling lies in more sophisticated multidisciplinary integration and the development of computational innovations, seeking to balance physical fidelity with operational feasibility through frameworks such as FINAM.

Keywords: Wildfire modeling, Coupled models, Fire-atmosphere interaction, Environmental simulation, Fire behavior prediction, Computational fire science

Modelos Acoplados para Simulación del Comportamiento de Incendios Forestales: Estado Actual y Tendencias Futuras

Resumen. Los incendios forestales son fenómenos complejos que implican interacciones dinámicas entre el fuego, la atmósfera, la vegetación y otros componentes ambientales. Para capturar esta complejidad y lograr simulaciones más realistas de la propagación del fuego y sus retroalimentaciones, la comunidad científica ha desarrollado modelos acoplados. Estos sistemas integran un modelo de comportamiento del fuego con otros modelos, como los meteorológicos o ecológicos. La evolución en el modelado ha progresado desde enfoques desacoplados con entradas estáticas hacia sistemas acoplados que capturan mecanismos dinámicos de retroalimentación. Principalmente, se distinguen dos categorías: los modelos acoplados cuasi-físicos que incorporan física fuego-atmósfera mediante relaciones semi-empíricas para tasas de liberación de calor y propagación, y los modelos basados en la física que representan el comportamiento del incendio a un nivel más sofisticado, resolviendo procesos de combustión con alta resolución. Las ventajas clave de los modelos acoplados radican en su capacidad para simular comportamientos extremos del fuego, como remolinos y columnas de convección elevadas, y para predecir el "spotting". Sin embargo, su limitación más significativa es la sustancial demanda computacional, lo que a menudo impide su uso en tiempo real para pronósticos operativos. El futuro del modelado acoplado se orienta hacia una integración multidisciplinar más sofisticada y el desarrollo de innovaciones computacionales, buscando equilibrar la fidelidad física con la viabilidad operativa a través de marcos como FINAM.

Palabras clave: Modelado de incendios forestales, Modelos acoplados, Interacción fuego-atmósfera, Simulación ambiental, Predicción del comportamiento del fuego, Ciencia computacional del fuego.

1. Introduction

Wildfire modeling has evolved from mid-20th-century empirical surface models (Rothermel, 1972) to sophisticated frameworks integrating fire-atmosphere interactions. The inherent multi-scale and multi-physics nature of wildfires, spanning from combustion chemistry to atmospheric effects, demands dynamic modeling capabilities. Consequently, modern simulation has shifted toward coupled models that surpass traditional static inputs, a necessity driven by climate change and expanding human development (Dunn et al., 2017; Méndez-Garabetti et al., 2016; Méndez Garabetti, 2022). Accurate simulation is thus essential for ecosystem protection, safety, and risk-based decision-making.

Coupled models enhance predictive capacity by integrating diverse modeling frameworks to represent interconnected fire dynamics. These tools aim to support firefighting and minimize damage by reproducing key characteristics such as spread rate, intensity, and heat generation. To overcome the limitations of individual schemes, this paper reviews strategies for integrating different wildfire simulators to improve prediction quality.

It is crucial to distinguish between terminologies: unlike "fire-atmosphere coupling,"which describes physical feedback loops between fire and meteorological models, this work focuses on "fire-fire coupling"(or multimodel ensembles).

This statistical integration aggregates predictions from diverse wildfire models to filter noise and enhance reliability, applying principles similar to meteorological ensemble forecasting.

The work is organized as follows: Section 2 outlines the history of coupled models; Section 3 surveys integrative approaches; Section 4 examines applications in research and management; Section 5 discusses extreme behavior and computational challenges; Sections 6 and 7 explore future directions and broad implications; and Section 8 summarizes key findings.

2. Evolution and Types of Coupled Fire Models

The evolution of fire models can be broadly classified into coupled and uncoupled models; the latter emerged in the 1990s as computational capabilities advanced (Coen, 2018). Uncoupled models, which predominated until that decade, did not include dynamic representations of atmospheric conditions or any other context. Instead, they relied on static meteorological data, local measurements, or atmospheric simulations (independent or offline) to predict fire behavior (Haupt et al., 2019). These models did not implement the relationship of heat release during combustion with atmospheric flow conditions near the fire front (Haupt et al., 2019). Coupled models can be classified into several categories depending on their computational approach and level of physical detail:

- Quasi-physical coupled models: These represent an intermediate class that incorporates fire-atmosphere physics while still obtaining heat release rates, fuel consumption, and spread rates from semi-empirical relations (Kochanski et al., 2013). Examples include CAWFE (Coupled Atmosphere-Wildland Fire-Environment), WRF-Sfire, and MesoNH-ForeFire (Kochanski et al., 2013). These models typically couple CFD-type weather models with semi-empirical fire spread models (Caus et al., 2018).
- Physics-based coupled models: These represent the most sophisticated approach, utilizing physics-based process models to represent wildfire behavior (Linn et al., 2002). Examples include FIRETEC and WFDS (Wildland-Urban Interface Fire Dynamics Simulator), which resolve elements of combustion processes and require much higher resolution with grid sizes of a few meters or less (Haupt et al., 2019). These models are based on approximations to the governing equations of fluid dynamics, combustion, and thermal degradation of solid fuels (Mell et al., 2007).

Increased computational power in recent decades has enabled more sophisticated coupling between fire and atmospheric models (McLauchlan et al., 2020). These coupled models can now capture complex landscape-scale fires over several days (Coen et al., 2018), while global models continue to improve their representation of fire frequency, burned area, and seasonality over longer timescales (McLauchlan et al., 2020; Hantson et al., 2016). A significant advantage of coupled models is their ability to simulate extreme fire behaviors, such as fire whirls, high convection columns, and rapid spread rates, which cannot be adequately represented with uncoupled approaches (Haupt et al., 2019). These models are particularly valuable for studying problems beyond the scope of empirical and semi-empirical models, such as wildland-urban interface fires, evaluating fuel treatments, and investigating the mechanisms underlying spreading fires (Mell et al., 2007). However, the increased complexity of coupled models entails significant computational demands that often prevent real-time prediction. In some ways, simpler models are still necessary for operational tools, while multidimensional models with different levels of coupling are better suited for post-event investigation and analysis (Santoni et al., 2011b), the challenge is bringing them down to operational levels. The evolution of fire modeling demonstrates a continuous improvement in our ability to represent the complex physics of fire-atmosphere interactions, with each new generation of models addressing the limitations of previous approaches by incorporating more detailed physical processes and dynamic feedbacks (Santoni et al., 2011a).

We can define a coupled fire-atmosphere model as a system in which a fire spread or behavior model and an atmospheric model are integrated to exchange information, allowing for the simulation of their mutual interaction. These models consist of several key components that work together to simulate the complex interactions between wildfires and the surrounding atmosphere. Essentially, these models integrate two main systems: an atmospheric model that simulates meteorological conditions and a fire spread model that simulates combustion and fire spread. (Kochanski et al., 2013) The atmospheric component typically employs computational fluid dynamics (CFD) to model air movement, temperature changes, and humidity dynamics in and above the boundary layer. (Hoffman et al., 2018) This component calculates wind fields, turbulence patterns, and thermodynamic properties of the atmosphere that influence fire behavior. Advanced models such as WRF (Weather Research and Forecasting), MesoNH, and other numerical weather prediction systems form the basis of the atmospheric component in many coupled systems. The fire spread component models combustion processes, heat release, and fire front propagation. This component varies in complexity, from simplified semi-empirical approaches to sophisticated physics-based models that directly simulate combustion chemistry. The fire component tracks the position of the fire front, typically using methods such as level tracking (in WRF-SFIRE) or tracer particles (in CAWFE) to represent the fire's advancing perimeter (Mandel et al., 2011; Clark & Coen, 2004).

3. Coupled Systems and Other Featured Models for Forest Fire Simulation

This section examines the distinctive features of notable coupled fire–atmosphere systems and other integrated platforms, as defined in the Introduction. It details their respective model types, simulation capabilities, computational performance, validation methods, and key applications to clarify the different forms of 'coupling' and 'integration' presented.

3.1. WRF-Sfire and WRFSC

WRF-Sfire is a comprehensive two-way coupled fire-atmosphere model built on the Weather Research and Forecasting (WRF) framework (Mandel et al., 2011). It estimates fire spread based on local meteorological conditions while accounting for the feedback between fire and atmosphere. The system is enhanced by a fuel moisture model that dynamically predicts moisture based on local meteorology, and it leverages WRF's nesting capabilities to resolve both large-scale synoptic flows and high-resolution fire behavior (Mandel et al., 2014). WRF-Sfire has demonstrated the ability to generate forecasts faster than real-time, positioning it as a potential operational tool. Its simulation capabilities include predicting fire spread, smoke dispersion, plume-top heights, fire emissions, and atmospheric chemistry. An expanded version, WRFSC, integrates WRF-Sfire with WRF-Chem to explicitly model smoke dispersion and its atmospheric chemistry effects, and has seen operational deployment in regions such as Israel (Mandel et al., 2014; Kochanski et al., 2016).

3.2. Coupled Atmosphere-Wildland Fire Environment (CAWFE)

The Coupled Atmosphere-Wildland Fire Environment (CAWFE) modeling system, often implemented as WRF-SFIRE, combines the Weather Research and Forecasting (WRF) numerical weather prediction model with a fire behavior and fuel consumption module (Coen et al., 2020). CAWFE establishes a two-way coupling where heat and water vapor fluxes from the fire alter atmospheric conditions—producing distinct fire winds—while the evolving atmosphere, in turn, influences the fire's behavior. To represent the advancing fire perimeter, CAWFE utilizes a tracer particle approach (Kochanski et al., 2013). The system has been progressively enhanced, for example, through the integration of dynamic fuel moisture models that allow for a more realistic representation of fire susceptibility and spread in response to atmospheric conditions.

3.3. FIRETEC

FIRETEC is recognized as one of the most advanced fire-scale coupled models, employing physics-based processes to represent wildfire behavior instead of relying on semi-empirical rules (Kochanski et al., 2013; Linn et al., 2002). This approach allows it to effectively model fires in complex terrain with non-homogeneous vegetation under realistic meteorological conditions. While these detailed simulations require significant computational resources, they enable virtual experiments that would be impossible or too risky in the physical world. The model has been applied to complex scenarios, such as assessing the impact of bark beetle-induced tree mortality on fire behavior. Its validation is often based on experiments co-designed by modelers and experimentalists to systematically assess model accuracy and uncertainties (Hoffman et al., 2018).

3.4. Wildland-Urban Interface Fire Dynamics Simulator (WFDS)

The Wildland-Urban Interface Fire Dynamics Simulator (WFDS) is another physics-based model that explicitly represents known fire processes by using approximations of the governing equations for fluid dynamics, combustion, and thermal degradation of fuels (Mandel et al., 2011; Ritter et al., 2020). Although more computationally demanding than empirical models, WFDS is particularly valuable for detailed virtual experiments. It has been validated against experimental data, including grassland fire experiments in Australia, showing favorable predictions of head fire spread rates across various wind speeds and ignition patterns (Mell et al., 2007). Its applications are well-suited for studying grassland fires, wildland-urban interface scenarios, and fires in heterogeneous fuel beds (Mell et al., 2007).

3.5. MesoNH-ForeFire

MesoNH-ForeFire is a quasi-physical coupled model that combines a CFD-type weather model (MesoNH) with a semi-empirical, front-tracking fire spread model (ForeFire) to capture fire-atmosphere interactions (Kochanski et al., 2013; Caus et al., 2018). Research with this system has focused on improving computational efficiency through methods like data assimilation and optimization. For validation, the model has been tested against idealized cases, such as simulations of perimeters expanding in concentric circles within a defined mesh, to verify its accuracy and performance (Caus et al., 2018).

3.6. Other Integration or Hybrid Simulation Approaches

Discrete Event System Specification (DEVS)-FIRE DEVS-FIRE utilizes the Discrete Event System Specification (DEVS) formalism to simulate wildfire spread and suppression (Wainer & Govind, 2024; Ntaimo et al., 2008). It integrates a cellular space model for fire spread with agent-based models for suppression activities, using real spatial data for fuels, terrain, and weather. The dynamic structure of the model enhances simulation performance, making it a candidate for real-time decision support in wildfire management (Wainer & Govind, 2024).

Vector-DEVS and ForeFire The Vector-DEVS approach offers a novel method for fire spread simulation by focusing on front-tracking without discretizing space into a grid of nodes (Wainer & Govind, 2024; Filippi et al., 2010). Unlike conventional methods with discrete time steps, Vector-DEVS advances time based on increments of physical quantities. This discrete-event approach, when coupled with physical fire rate-of-spread models, allows for efficient simulation of fire dynamics over large scales with high resolution, even on standard personal computers (Filippi et al., 2010).

While physics-based coupled models continue to advance, traditional operational tools based on Rothermel's fire spread rate formulas remain crucial for practical applications. Platforms such as BehavePlus, FARSITE, and PROMETHEUS employ uncoupled approaches that rely on static weather inputs rather than dynamically computing fire-atmosphere interactions (Mandel et al., 2011; Ager et al., 2011). These tools are favored for their computational efficiency in operational contexts, although they cannot capture the complex fire behaviors that emerge from the tight coupling between fire and atmosphere (Caus et al., 2018).

4. Applications and Implementations

Coupled fire-atmosphere models have been implemented across a broad spectrum of scientific investigations and practical applications, enabling researchers and fire managers to address complex questions that were previously difficult to explore. These applications encompass both research-oriented investigations and operational tools designed to support decision-making processes. In forest ecology research, physics-based models like WFDS-PB have been instrumental in investigating fine-scale pattern-process linkages between forest structure and fire behavior. For example, these models have been used to examine how local arrangements of canopy fuels influence heat transfer from surface fires to tree crowns, helping to explain fire effects in frequent-fire forests (Ritter et al., 2020). These "virtual experiments.ªllow researchers to study processes that would be impossible, too costly, time-consuming, or risky to investigate through field studies (Hoffman et al., 2018; Ritter et al., 2020; Dickman et al., 2023).

In the realm of fire-vegetation interactions, researchers have developed approaches to couple fire simulators with forest growth models. While some implementations simply link these models sequentially, more sophisticated approaches run fire and forest growth simulations in parallel to quantify impacts of management intensification and allow for reassessing risk throughout simulation periods (Barreiro et al., 2021). These coupled models support economic analyses of different management scenarios under fire risk—applications that had not previously been possible (Barreiro et al., 2021). For wildlife and ecosystem management, tools like HexFire have been developed to overcome traditional bottlenecks in linking fire simulators with ecological forecasting models. By integrating fire simulation directly within ecological modeling frameworks, these systems enable more seamless connectivity, population viability, gene flow, and disease spread analyses in fire-prone landscapes (Schumaker et al., 2022). Climate change assessment represents another significant application area, with projects like FIRE-PATHS coupling dynamics, climate modeling, and wildfire behavior simulation to assess future wildfire danger under changing climate conditions. Similarly, research efforts are establishing mechanistic linkages between plant water and carbon dynamics and fire behavior, working toward improving global fire forecasting through more process-based approaches (Dickman et al., 2023).

Operational implementations frequently focus on integrating multiple datasets, models, and user interfaces into decision support systems. The Integrated Fuels Treatment Decision Support System (IFT-DSS), for example, was developed to support efficient implementation of fuel treatment programs by integrating various prediction models for fire behavior, fuel consumption, and ecological effects (Reinhardt & Dickinson, 2010). These operational tools typically employ multiple fire behavior models—including NEXUS, FVS-FFE, FARSITE, FlamMap, BehavePlus, and FSIM—to account for uncertainty in wildfire events regarding timing, location, intensity, and duration (Ager et al., 2011). Recent advancements in coupled modeling applications include methods for assimilating real-time fire perimeter data into coupled fire-atmosphere models, ensuring that fire and atmospheric components remain synchronized (Kochanski et al., 2023). Additionally, enhanced approaches to wildfire simulation are incorporating comprehensive environmental data such as forest maps, terrain elevation, and historical weather patterns to create richer simulation environments (Ramadan, 2024). Coupled models have also found applications in real-time decision support for wildfire management. The dynamic structure implementation of DEVS-FIRE, for instance, improves simulation performance and supports real-time decision making through its ability to efficiently process high-resolution geospatial data (Wainer & Govind, 2024; Ntaimo et al., 2008). Similarly, Vector-DEVS has demonstrated the capability to perform large-scale, high-resolution simulations on standard personal computers in short timeframes, making it valuable for time-sensitive operational applications (Wainer & Govind, 2024; Filippi et al., 2010).

5. Advantages and Limitations of Coupled Models

Coupled fire-atmosphere models advance beyond traditional approaches by accounting for dynamic interactions where combustion heat alters atmospheric flow (Haupt et al., 2019). Their primary advantage lies in capturing extreme behaviors, such as fire whirls and convection columns, which emerge naturally from physical feedbacks rather than empirical prescriptions (Coen, 2018; Haupt et al., 2019). Furthermore, they significantly improve the prediction of spotting by modeling the convective transport of firebrands (Haupt et al., 2019; Martin & Hillen, 2016), offering enhanced predictive capabilities across various scales (Santoni et al., 2011b; Butler & Dickinson, 2010).

However, substantial computational requirements often preclude real-time forecasting (Haupt et al., 2019; Santoni et al., 2011b). High-resolution physics-based models (e.g., FIRETEC) are restricted primarily to research (Kochanski et al., 2013), and even "quasi-physical"models like WRF-Sfire face constraints despite relying on semi-empirical relations (Kochanski et al., 2013). Consequently, high-resolution requirements limit these applications to relatively small regions (Makar et al., 2021). Additionally, complex implementation creates a trade-off between sophistication and usability (Barreiro et al., 2021). Therefore, while coupled models advance scientific understanding, simpler uncoupled models (e.g., BehavePlus, FARSITE) remain essential for operational fire management (Caus et al., 2018; Santoni et al., 2011b).

6. Future Perspectives and Research Directions

The future of coupled fire-atmosphere modeling is moving toward increasingly sophisticated integration of multidisciplinary approaches and data sources. A primary direction identified by researchers is the continued development of two-way coupled models that better integrate weather prediction and fire propagation components (Silva et al., 2022). This trajectory builds upon existing systems like WRF-SFIRE, which has already demonstrated significant improvements in representing fire-atmosphere interactions through enhanced coupling with moisture dynamics and atmospheric chemistry (Mandel et al., 2014). An emerging area of research focuses on establishing mechanistic linkages between plant water and carbon dynamics and fire behavior. These connections, which influence combustion and heat transfer processes critical to determining plant survival, are increasingly recognized as essential components for improving the fidelity of coarse-scale global fire forecasting models (Dickman et al., 2023). The wildland fire research community has emphasized the value of process-based models for exploring potential mechanisms driving fire dynamics under novel climate conditions (Hoffman et al., 2018; Dickman et al., 2023).

Computational innovations are being developed to address the substantial processing requirements that have traditionally limited the operational application of coupled models. Research has demonstrated that even with straightforward coupling methods, atmospheric models can effectively simulate fire-induced dynamics and their effects on fire behavior, producing results comparable to more complex physics-based approaches like FIRETEC (Santoni et al., 2011b). This suggests that simplified but effective coupling strategies may provide a pathway to operational implementation without sacrificing essential physical representations. The integration of comprehensive environmental datasets represents another significant direction for future development. Enhanced wildfire simulation approaches are increasingly incorporating detailed forest maps, terrain elevation, and historical weather patterns to create richer simulation environments (Ramadan, 2024). This data-intensive approach aligns with sophisticated modeling systems for studying wildland fire behavior and helps bridge the gap between research and operational applications. Cellular automata (CA) models are evolving as another promising direction, with researchers exploring approaches to enhance their physical fidelity. By coupling CA models with existing forest physical models, researchers have demonstrated improved accuracy in fire spread simulation (Trucchia et al., 2020; Collin et al., 2011). The modular nature of CA models allows them to incorporate increasingly sophisticated physical processes while maintaining computational efficiency, making them potential candidates for next-generation operational tools.

At landscape scales, researchers continue to develop models relevant to forest management that integrate fire behavior with ecological dynamics. Systems like FIRE-BGC and LANDIS-II represent steps toward linking fire behavior with broader ecological processes (Dickman et al., 2023). These integrated approaches may eventually be coupled with fine-scale fire behavior models using advanced fuel modeling frameworks such as Fuel3D, FuelManager, and STANDFIRE

(Dickman et al., 2023). Despite these advancements, the computational demands of multidimensional coupled models continue to present challenges for real-time forecasting applications (Santoni et al., 2011b). Finding the right balance between model complexity and operational viability remains a central challenge, with researchers working to develop systems that maintain physical realism while meeting the time-sensitive requirements of fire management operations. As computing power increases and modeling techniques advance, the gap between research-oriented coupled models and operationally viable tools is expected to narrow (Pais et al., 2019).

7. Discussion

This comprehensive review has charted the significant evolution of forest fire behavior simulation, firmly establishing the indispensable role of coupled models in moving beyond the limitations of earlier, often disconnected, empirical approaches Rothermel, 1972. The trajectory towards integrating fire dynamics with atmospheric, ecological, and other environmental systems signifies a deeper understanding of wildfires as complex, multi-faceted phenomena. The capacity of these models to simulate previously intractable aspects, such as fire-atmosphere feedbacks and the emergence of extreme fire behaviors, represents a pivotal advancement with profound implications not only for fundamental fire science but also for practical risk assessment and ecosystem management in a world facing escalating wildfire threats Dunn et al., 2017; Coen, 2018; Haupt et al., 2019.

The discussion about the tension between high physical fidelity and computational feasibility finds promising insight in the emergence of frameworks such as FINAM (FINAM Is Not A Model) (Müller et al., 2024). By simplifying the coupling process and managing the complexity inherent in coupled models, FINAM mitigates the computational barrier and facilitates the integration of diverse models. This is crucial for the effective translation of cutting-edge research into reliable and accessible operational tools. Although FINAM does not eliminate the need for validation and uncertainty quantification, its focus on interoperability and automatic handling of metadata and units can contribute to data consistency and, therefore, more robust validation. It represents an effort to address the socio-technical challenges of fire modeling by offering a solution that enables greater agility in the development and deployment of holistic simulation systems. The diversity of coupling methodologies and simulation platforms (e.g., WRF-Sfire, FIRETEC, CAWFE) reviewed herein (Linn et al., 2002; Mandel et al., 2011; Coen et al., 2020) reflects the multifaceted nature of the research questions being addressed—from fine-scale physics to landscape-level ecological impacts. However, this diversity also highlights a central and persistent tension: the trade-off between achieving high physical fidelity and maintaining computational feasibility (Santoni et al., 2011b). While physics-based models offer unparalleled insight into the fundamental processes governing fire spread and intensity (Haupt et al., 2019; Linn et al., 2002), their intensive computational demands remain a significant barrier to their widespread operational use, particularly for real-time forecasting where rapid outputs are crucial. This necessitates a continued, pragmatic reliance on a spectrum of modeling tools, including simpler, uncoupled systems for certain operational contexts, despite their known limitations (Ager et al., 2011).

Furthermore, the increasing complexity of coupled models introduces considerable challenges related to parameterization, validation, and the robust quantification of uncertainty. Accurately representing diverse fuel complexes, dynamic fuel moisture, and micro-scale atmospheric interactions across varied global ecosystems requires extensive, high-quality input data and sophisticated submodels, which are not universally available or validated (Kochanski et al., 2016; Dickman et al., 2023). While validation against specific experimental burns or well-documented wildfires is undertaken for many models (Kochanski et al., 2013; Mell et al., 2007), the comprehensive validation of these intricate systems across the full gamut of potential fire environments remains a formidable scientific and logistical task. The propagation of uncertainties from input parameters, model structure, and coupling mechanisms through the simulation chain critically affects the reliability of predictive outputs, an issue of paramount importance for decision-making under risk.

Despite these challenges, the expanding array of applications—from supporting tactical fire management decisions with real-time data assimilation (Caus et al., 2018; Kochanski et al., 2023) to informing long-term strategic planning for fuel treatments and climate change adaptation (Barreiro et al., 2021)—underscores the transformative potential of coupled modeling. The ongoing research eforts aimed at integrating more comprehensive environmental data, leveraging advances in high-performance computing, and incorporating data-driven techniques like machine learning, are indicative of the dynamism in the field (Santoni et al., 2011b; Ramadan, 2024; Silva et al., 2022). These endeavors are crucial not merely for incremental improvements but for fundamentally advancing our ability to predict and manage wildfire behavior.

Ultimately, the effective translation of cutting-edge research in coupled modeling into reliable, accessible, and widely adopted operational tools is a complex socio-technical challenge. It requires sustained interdisciplinary collaboration, targeted investment in overcoming key scientific and computational hurdles, and a commitment to rigorous validation and uncertainty characterization. This review highlights that while the journey is ongoing, the progress made provides a robust foundation for developing more holistic and actionable wildfire simulation systems capable of addressing the pressing needs of modern fire management.

8. Conclusions

This work has synthesized the status and prospects of coupled models in wildfire simulation. A key conclusion is that coupled approaches represent a significant advance over traditional methods by incorporating dynamic feedback mechanisms between fire and its environment. This enables the characterization of complex phenomena such as extreme fire behavior and spotting. A diverse range of platforms has been developed, from detailed physics-based systems (e.g., FIRETEC, WFDS) to quasi-physical models (e.g., WRF-Sfire, CAWFE), tailored to different research objectives.

However, the substantial computational cost remains the primary challenge limiting widespread operational adoption, often restricting these models to research or post-event analysis. Despite this gap between modeling capabilities and real-time decision support, coupled models have demonstrated considerable value in ecological understanding, risk assessment, and fuel management. Real-time data assimilation into these models shows particular promise for future operational utility.

To address the tension between physical fidelity and feasibility, future research moves toward sophisticated multidisciplinary integration. Key directions include computational innovations—such as HPC-enabled solvers and reduced-order surrogates—which are crucial for enabling real-time forecasting. More sophisticated multi-domain integration is also being sought, linking fire models with ecosystem dynamics, hydrology, and air quality to assess cascading impacts. Furthermore, improved dynamic data assimilation integrating observations from satellites and drones will be critical for improving prediction accuracy and quantifying uncertainty.

In this sense, frameworks like FINAM exemplify efforts to mitigate computational barriers by simplifying model integration and promoting interoperability. Ultimately, the creation of user-centered operational tools—such as modular cloud platforms with intuitive interfaces—and the fostering of open standards are essential to bridge the gap between research-level simulations and operational wildfire management. Sustained development in these areas is crucial to improving preparedness and response in an era of increasing fire risk.

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