# Fire in Paradise[1]: Mesoscale Simulation of Wildfires

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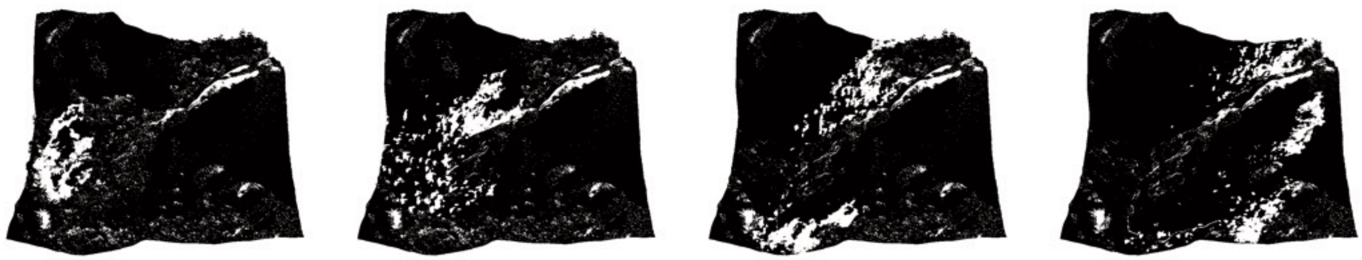

Fig. 1. Simulation of a wildfire spreading in the valley around Half Dome in California's Yosemite National Park. Using our framework, this scene can be simulated at interactive rates allowing the user to conveniently explore the wildfire.

Resulting from changing climatic conditions, wildfires have become an existential threat across various countries around the world. The complex dynamics paired with their often rapid progression renders wildfires an often disastrous natural phenomenon that is difficult to predict and to counteract. In this paper we present a novel method for simulating wildfires with the goal to realistically capture the combustion process of individual trees and the resulting propagation of fires at the scale of forests. We rely on a state-of-the-art modeling approach for large-scale ecosystems that enables us to represent each plant as a detailed 3D geometric model. We introduce a novel mathematical formulation for the combustion process of plants – also considering effects such as heat transfer, char insulation, and mass loss – as well as for the propagation of fire through the entire ecosystem. Compared to other wildfire simulations which employ geometric representations of plants such as cones or cylinders, our detailed 3D tree models enable us to simulate the interplay of geometric variations of branching structures and the dynamics of fire and wood combustion. Our simulation runs at interactive rates and thereby provides a convenient way to explore different conditions that affect wildfires, ranging from terrain elevation profiles and ecosystem compositions to various measures against wildfires, such as cutting down trees as firebreaks, the application of fire retardant, or the simulation of rain.

[1]The title 'Fire in Paradise' is chosen in memory of the Camp Fire that devastated the town Paradise in Northern California's Butte County, November 8–25, 2018, resulting in more than 80 fatalities. A 2019 documentary film directed by Zackary Canepari and Drea Cooper carries a similar title.

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## 1 INTRODUCTION

In recent years, climate change has facilitated an inexorable increase of bigger and more intense wildfires across the globe. Understanding the complex interplay of fires and large-scale ecosystems plays a key role in preventing wildfires and in containing them. To this end, we argue that simulating wildfires with detailed geometric models of terrain and vegetation along with physically plausible fluid dynamics can serve as an essential tool for understanding wildfires and for predicting their outcome. However, realistically simulating wildfires in different ecosystems, also considering the wide range of geometric compositions of trees and plants, their inhomogeneous material properties, as well as the interaction of a fire and the atmosphere, is a challenging and open problem.

While a wide range of methods exists to plausibly model branching structures [Měch and Prusinkiewicz 1996; Palubicki et al. 2009; Pirk et al. 2012b; Stava et al. 2014], only very recently methods also focus on the realistic simulation of dynamic behavior and physics response of plant models, including the simulation of growth [Longay et al. 2012], surface adaptation [Hädrich et al. 2017], the interaction with wind [Pirk et al. 2014], or based on realistic material properties [Wang et al. 2013; Zhao and Barbič 2013]. Previous work has combined ecosystem and terrain erosion simulation for authoring landscapes [Cordonnier et al. 2017]. This avenue of research has been expanded modeling large-scale ecosystems [Kapp et al. 2020; Makowski et al. 2019], and terrain features, such as avalanches [Cordonnier et al. 2018] or glaciers [Argudo et al. 2020]. Together, these methods provide a testament that efforts trend toward physically plausible and specialized approaches to simulate natural phenomena.

Most of the current methods for simulating combustion processes do not specifically focus on tree or wood combustion and therefore cannot be easily applied to models of trees and plants [Melek and Keyser 2002]. Methods in other research disciplines, such as material sciences or forestry, specifically focus on wildfires or the resistance of trees to fires. However, these methods are often computationally demanding and only focus on the combustion of wood samples in laboratory setups [Thi et al. 2016] or employ severely simplified geometric representations of trees and plants [Seidl et al. 2012], such as a suspended cloud of spherical Lagrangian particles that represent either foliage or wood [Mendoza et al. 2019]. Closest to our work is the method of Pirk et al. [2017], who discretize branches as triangular surface meshes that enable the simulation of tree combustion with an astounding degree of detail for complex branching structures at interactive rates. However, while their work focuses on the combustion of individual tree models, we aim to simulate wildfires at forest scale, which cannot be realized with their representation.

In this paper, we advance the field of wildfire simulations by introducing a novel mathematical formulation that allows us to simulate the combustion of trees at an intermediate scale using detailed geometric models. We employ the method of Makowski et al. [2019] to simulate ecosystems. Each tree model is composed of a number of self-organizing branch templates that define its 3D branching structure. Collections of trees can grow together, which results in diverse and realistic branching structures for individual tree models in the ecosystem, while each module is reused across the same tree and for all other trees, which enables efficient modeling and rendering. An advantage of a module-based tree representation is that it provides a convenient way to control the level of detail for representing trees. A tree can either be represented by a large number of very detailed modules, which allows us to generate complex and highly realistic branching structures, or – to the opposite effect – by only a few coarser modules to represent each tree in a lightweight and thus more efficient manner.

To simulate tree combustion we use this module-based representation for trees in two ways: (1) we simulate the combustion at the branch level for each module. This allows us to capture various effects necessary to realistically simulate the combustion of individual branches, including char insulation, mass loss, and heat transfer; (2) we compute the combustion of wood – also known as pyrolysis – across the entire tree at module-scale. A collection of modules that represent a tree model is defined as a directed graph. Once the combustion of a single module progresses toward an adjacent module, the combustion is propagated to this module and continued for this module's branching structure.

Our goal is to jointly simulate fire and the combustion of large collections of plants – a computationally demanding undertaking. To capture the spread of fire across the entire ecosystem we use a volumetric grid-based fluid solver that enables us to transfer heat from the environment to individual plants. A burning plant – in turn – releases heat to its environment, which triggers a feedback loop that maintains the combustion and that may cause the spread of fire from one plant to another. A key advantage of our wildfire model is that the combustion of plant tissue and the simulation of fire are decoupled: Trees can be represented with a varying number of modules, while fire can be computed with more or less detailed volumetric grids. This allows us to manage the complexity required for wildfire simulations, while maintaining the realistic and physically plausible interaction of trees and fire. An example of a complex wildfire simulation is shown in Figure 1. In this contribution, we do not address fire spread on the ground facilitated by grass, branch litter, and undergrowth vegetation. Moreover, the role of leaves is ignored and the modeling of sparks flying through the air is left for future work.

In summary, our contributions are as follows: (1) we introduce a novel combustion model for individual trees based on branch modules that allows us to realistically simulate wood pyrolysis; (2) we propose a hybrid model capturing heat transfer between individual branch modules and the environment allowing to appropriately capture fire spread; (3) we capture cloud and rain phenomena within our wildfire simulator by extending the Kessler model; (4) we simulate wildfires of more than 100K individual plants represented by complex and detailed geometry; (5) we show that our interactive framework enables us to explore the emergence of wildfires in ecosystems of different composition and ways to counteract the spread of fire.

## 2 RELATED WORK

With our goal to simulate wildfires for individual and detailed models of trees our work is related to methods that aim at generating complex and realistic models of terrains, the modeling of vegetation, as well as the simulation of fire or – more generally – fluid dynamics. While this spans a breath of work that we cannot conclusively discuss, our goal is to provide an overview for these research directions with a focus on tree and terrain modeling.

*Modeling Trees and Plants.* Many of the early approaches for modeling trees and plants have focused on defining the internal properties of trees, such as branching angles and internode lengths to model branching structures [Aono and Kunii 1984; Kawaguchi 1982; Oppenheimer 1986; Smith 1984]. Later, biologically plausible methods were introduced that allow us to model the many variants of tree form in more nuanced and principled ways [Bloomenthal 1985; Weber and Penn 1995] and based on defining the developmental process of plants [de Reffye et al. 1988]. Furthermore, L-systems [Prusinkiewicz 1986] and rule-based techniques [Lintermann and Deussen 1999] have been recognized as powerful modeling approaches for diverse shapes of trees and plants.

To further increase the realism, a few methods also aim at modeling the environmental response of plants during their development [Měch and Prusinkiewicz 1996; Palubicki et al. 2009; Pirk et al. 2012b; Stava et al. 2014]. Besides the forward modeling of branching structures, reconstructing trees and plants based on images [Argudo et al. 2016; Neubert et al. 2007; Quan et al. 2006; Reche-Martinez et al. 2004; Tan et al. 2008] or point clouds [Livny et al. 2011; Xu et al.

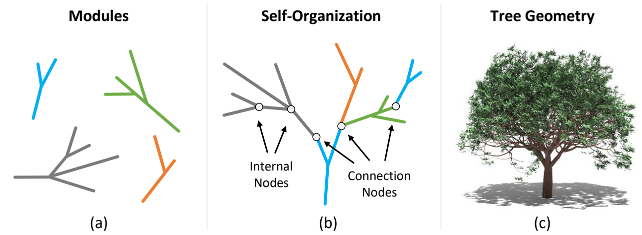


Fig. 2. We use a module-based representation for plants. Each plant is defined as a combination of modules (a). Modules are adapted through self-organization during ecosystem development and are reused across the same plant and the entire ecosystem (b). Once the branch graph has been defined we generate the final plant geometry (c).

2007] also provides a convenient alternative to capture complex plant form. Sketch-based approaches on the other hand enable the refined generation of tree models, while also supporting artistic requirements toward content creation [Chen et al. 2008; Longay et al. 2012; Okabe et al. 2007; Wither et al. 2009]. More recently, a number of methods simulate the physics-response and the dynamics of tree models, including the swaying of trees in wind fields [Habel et al. 2009; Pirk et al. 2014], the interactive modeling of growth [Hädrich et al. 2017; Pirk et al. 2012a], or the simulation of tree dynamics based on physically plausible materials [Wang et al. 2013; Zhao and Barbič 2013] or through machine learning-assisted iterative solvers [Shao et al. 2021].

*Terrain Models and Plant Ecosystems.* Generating detailed models of complex terrain has been extensively studied in computer graphics [Fournier et al. 1982; Kelley et al. 1988]. Early approaches for modeling photo-realistic terrains mostly focus on generating complex natural landscapes by employing fractals [van Lawick van Pabst and Jense 1996], noise functions [Perlin 1985], or procedural models [Ebert et al. 2002]. For plant ecosystems, existing methods not only aim at finding ways to compute realistic distributions of various species [Deussen et al. 2002, 1998; Lane and Prusinkiewicz 2002], but also to identify representations for ecosystems that enable modeling and rendering at scale; methods range from voxels [Jaeger and Teng 2003] and volumetric textures [Bruneton and Neyret 2012] to layers [Argudo et al. 2017] and branch templates [Makowski et al. 2019]. To support the design and content creation of terrain and ecosystems a number of methods also explore sketch-based interfaces in conjunction with biological priors [Beneš et al. 2009]. We refer to the recent survey by Galin et al. [2019] for a more detailed overview on terrain modeling. It is worth pointing out that real-world data and machine learning has been leveraged using generative adversarial networks trained by real-world terrains and their sketched counterparts [Guérin et al. 2017], or by deriving a canopy height model combined with an understory layer resulting in realistic ecosystems [Kapp et al. 2020].

Due to the enormous amount of geometry required to realistically generate plant ecosystems a number of methods focus on level of detail strategies. Prominent examples include point and line representations [Deussen et al. 2002; Stamminger and Drettakis 2001], billboard clouds [Behrendt et al. 2005], or stochastic simplification [Cook et al. 2007; Neubert et al. 2011]. To efficiently model large-scale ecosystems, we employ the method of Makowski et al. [2019] that represents trees as collections of branch modules that can be efficiently instantiated to model and render large collections of plants, while the full branch geometry of individual tree models is retained.

*Simulating Fire and Combustion.* The computation of fluid dynamics as required for simulating fire has a long tradition in computer graphics research [Bridson 2008]. Most approaches rely on grid-based fluid solvers to capture turbulence as one of the predominant features of fire [Hong et al. 2010; Nguyen et al. 2002; Stam 1999] or smoke [Fedkiw et al. 2001; Pan and Manocha 2017; Rasmussen et al. 2003]. Furthermore, a number of methods explicitly focus on rendering fires either based on physically-accurate models [Nguyen et al. 2002; Pegoraro and Parker 2006] also with respect to specific flame properties [Nguyen et al. 2001], with an emphasis on artistic control [Lamorlette and Foster 2002], or based on combined representations that also use particles to simulate turbulence [Horvath and Geiger 2009].

Similar to simulating fire, the process of combustion is often modeled based on planar or volumetric grids that enable to not only model the distribution of heat [Melek and Keyser 2002] on surfaces [Chiba et al. 1994] or in volumes [Zhao et al. 2003], but also to simulate fire across disconnected propagating fronts [Liu et al. 2012]. Simulating combustion and heat diffusion for articulated and continuously defined surface geometry remains a challenging problem, which is only addressed by a few methods [Hong et al. 2010]. Material point methods, on the other hand, have recently gained popularity capturing thermodynamic properties to simulate phenomena such as the melting or solidifying of materials [Stomakhin et al. 2014]. However, most of these methods are not defined to simulate wood combustion at ecosystem scale.

*Wood Combustion and Wildfires.* In forestry, botany, and material science a substantial amount of work focuses on the combustion of wood and plants. Existing methods range from simulating heat transfer [Encinas et al. 2007], charring [Lizhong et al. 2002], or the pyrolysis process of entire trees and plants [Bohren and Thorud 1973]. A key factor for understanding the propagation of fire in forests is the fire resistance of plants. Hence, a number of approaches aim at modeling the resistance of individual species [Lawes et al. 2011], the impact of canopy architecture on flammability [Schwilk 2003], or the moisture content of plant material [Masinda et al. 2020]. A large body of work focuses on simulating wildfires, often with the goal to establish predictive models [Monedero et al. 2017; Pastor et al. 2003; Richards 1990], to simulate fires for different biomes [Cheney et al. 1993; Dupuy and Larini 2000], to understand smoke properties and the ignition of wildfires [Anand et al. 2017; Gustenyov et al. 2018], to predict high-fidelity flows around strongly simplified trees [Mendoza et al. 2019], or by specifically focusing on the coupling of wildfires and the atmosphere [Coen 2005; Sun et al. 2009]. Finally, researchers also investigate the long-term growth response of vegetation to wildfires [Chileen et al. 2020]. Similar to our work, many of these approaches aim at defining accurate models for wood combustion or physically-accurate solvers for wildfires. However, unlike these methods, we simulate wood combustion for