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Human Mediation of Wildfires and Its Representation in Terrestrial Ecosystem Models

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Abstract

Increasing wildfires are causing global concerns about ecosystem functioning and services. Although some wildfires are caused by natural ignitions, it is also important to understand how human ignitions and human-related factors can contribute to wildfires. While dynamic global vegetation models (DGVMs) have incorporated fire-related modules to simulate wildfires and their impacts, few models have fully considered various human-related factors causing human ignitions. Using global examples, this study aims to identify key factors associated with human impacts on wildfires and provides suggestions for enhancing model simulations. The main categories explored in this paper are human behavior and activities, socioeconomic background, policy, laws, regulations, and cultural and traditional activities, all of which can influence wildfires. Employing an integrated and interdisciplinary assessment approach, this study evaluates existing DGVMs and provides suggestions for their improvement.

Keywords: wildfires; human ignitions; dynamic global vegetation models (DGVMs); human behaviors; socioeconomic factors

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1. Introduction

The large wildfires in recent years, for example in Canada (2023), Siberia (2022), California and Nevada (2023 and 2024), Australia (2019 and 2020), and Hawaii (2023), cause concern about future ecosystem functioning and services [1–3]. Most recently, in January 2025, California experienced one of the most severe winter wildfires on record. Unseasonably dry conditions, high winds, and persistent drought contributed to rapid fire spread across parts of Southern California. Thousands of residents were evacuated, several hundred structures were damaged or destroyed, and the fires caused significant disruption to ecosystems and local air quality [4]. The need to improve the understanding and prediction of wildfires is undoubtedly increasing. In contrast to prescribed burning, which is a planned activity to mitigate the effect wildfires or for biodiversity management of fire-dependent ecosystems [5,6], wildfires refer to the unintentional and often uncontrolled fires occurring in natural or semi-natural landscapes, such as forests, grasslands, and savanna [7–9]. Wildfires can have both positive and negative effects on terrestrial functioning and ecosystem services (Figure 1). Extreme fires can burn the biomass and fuel load, increasing carbon emissions into the atmosphere and thus enhancing global warming [10,11]. Over longer timescales however, wildfires can promote soil carbon sequestration, reduce atmospheric carbon dioxide concentrations, and promote atmospheric oxygen levels by producing natural biochar in the soils [12].

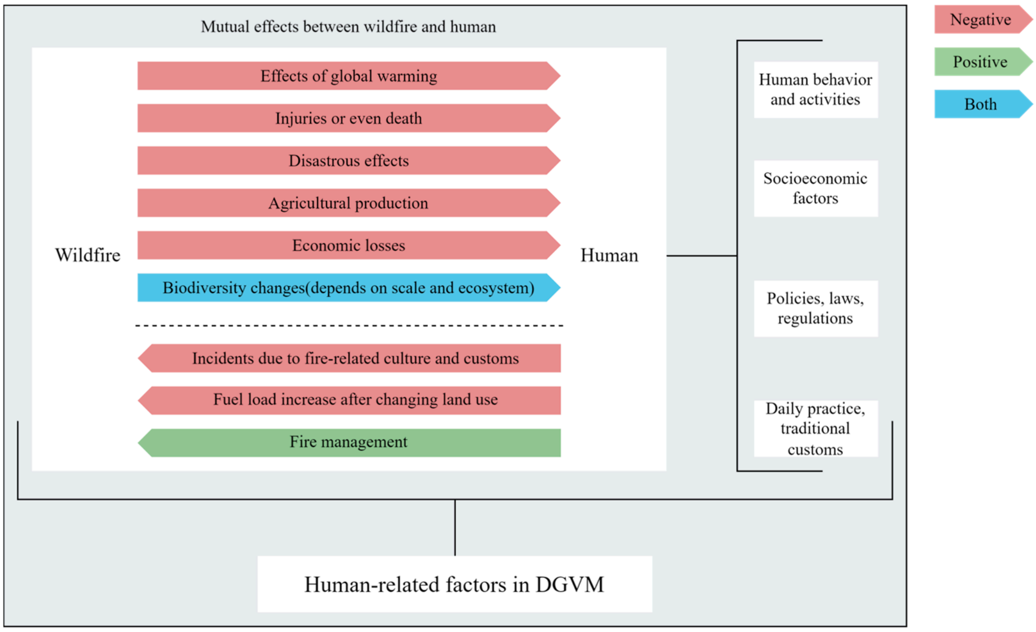

Figure 1. Human-related factors connected with wildfires impacting ecosystem functioning and biodiversity in negative or positive ways.

While catastrophic fires can have disastrous effects on ecosystems that are not adapted to frequent fires [13], some small-scale fires, including prescribed burning, are important for maintaining biodiversity and conserving endangered species in ecosystems adapted to fire [14]. In regions like the Western Mediterranean, shifting fire regimes due to climate change have fostered the growth of drought-resistant species [15]. In addition, prescribed fires effectively reduce the incidence of pests and diseases by suppressing the spread of forest pathogens and pests [16,17]. Furthermore, by reducing fuel loads, prescribed fires significantly lower the likelihood of high-risk wildfires [18]. Low-intensity fires enhance soil nutrient availability through the “ash bed effect,” thereby increasing land productivity [19].

Wildfires can be detrimental to local economies, as they may cause losses of valuable material (e.g., wood or crops), infrastructure (e.g., buildings or wooden electricity poles), and other goods, and sometimes result in human casualties.

Although there have been wide annual variations, there have been several large wildfires around the world in recent years [20]. These can be largely accounted for by ongoing global warming and increasing human interventions, like changes in land use and fire management strategies [21]. Due to climate change, many parts of the world have experienced warmer and longer drought seasons [22], which have triggered more frequent ignitions and larger burned area in, for example, Australia [23], the Mediterranean area [24], and the Pacific U.S. [25], as well as in high latitude boreal forests in the Northern Hemisphere [26]. In addition, changes in land use (e.g., forestation, deforestation, land abandonment, urban expansion) and unsuccessful attempts at fire-related policy may also trigger fire ignitions [27]. Human activities can influence wildfire regimes across the world in many aspects through land use changes [28,29], fire management plans and strategies [30–32], which will be better understood by acknowledging the social, cultural, and economic background [32–34].

Human interventions can impact fire regimes in many ways, and we will emphasize the following three aspects (see also Figure 1). Changes in land use types have an impact on fire regimes. The conversion of natural landscapes, such as forests and grasslands, to agricultural and urban use can lead to changes in vegetation types and structures. These changes can make some areas, like the wildland–urban interface (WUI) zone, more susceptible to fire risks [35,36]. Land use abandonment may, however, also increase the risk of more wildfires, for example, when the fuel load is built up through succession or when agricultural areas are invaded by fire-tolerant grasslands [37].

Fire management practices also exert strong impacts. People living in WUI areas are more likely to face wildfire hazards, and therefore, there is a need to plan and manage local fire regimes. People living in the communities can actively engage in fire prevention and management plans, to mitigate the risk and consequences of wildfires [38,39]. Similarly, carefully planned burning activities can sometimes decrease the occurrence of catastrophic wildfires [40,41], and for some ecosystems benefit biodiversity [42].

Different cultures and customs also have an impact on the occurrence and spread of wildfires. Some may use fire in religious and traditional contexts, such as in China [43,44]. At the same time, social background may also impact fire regimes in different communities [45]. Lastly, the different countries' financial opportunities and varying ability to prepare for and organize firefighting are of course an important backdrop to understanding the risks and effects of wildfires when they first occur.

Dynamic global vegetation models (DGVMs) describe and implement dynamics of vegetation processes, such as photosynthesis, phenology, establishments, and mortality. DGVMs take a process-based approach and have been developed and widely applied to simulate large-scale changes in plant functional types in response to natural climate changes and human forcing, such as land use changes. DGVMs have also been integrated into land surface models coupled with Earth System Models (ESMs) to better understand vegetation–climate feedback and improve future climate projections [46]. As an important disturbance in terrestrial ecosystems, wildfire-related processes have since the early 2000s been incorporated into DGVMs (referred to as fire-enabled DGVMs) to simulate the occurrence and spread of wildfires, as well as to quantify their impact on terrestrial ecosystems [47]. Fire-enabled DGVMs have evolved over the past few decades to become an important component in understanding and simulating fires, globally and historically [48]. They have also become an important tool for projection of future wildfire-related risks, complementary to more statistical approaches [49]. The DGVMs provide valuable insights into the interactions and feedback between wildfires, the climate, and vegetation, and also human interventions, which may be beneficial for assessing the comprehensive impact of fire and for developing fire management plans and strategies. Nevertheless, large uncertainties and biases remain in simulating the occurrence and extent of wildfires in DGVMs [50], as well as their ecological consequences. This can be largely attributed to the lack of observational data to parameterize and constrain both the natural and human factors related to wildfire processes.

Even though many studies acknowledge the important role of humans in wildfire ignition and suppression, human intervention has been crudely described or even overlooked in many of the fire-enabled DGVMs. In recent years, there has been growing evidence and knowledge of how human behaviors relate to wildfires [51]. Novel fire risk assessments and human intervention technology are also emerging [52]. This highlights the need for a reevaluation of the current implementation of human factors related to wildfires in DGVMs.

Moreover, recent developments regarding coupling of DGVMs with Integrated Assessment Models (IAMs), allow and require more comprehensive consideration of human dimensions, such the exposure and vulnerability of human society to wildfires and the socioeconomic impacts of wildfires. Wildfires suppress GDP growth and employment, particularly in tourism, retail, agriculture, and so on [53]. In Southern Europe, affected regions face substantial annual GDP losses, amounting to billions of euros [54].

This paper aims to examine various aspects of human intervention and how human intervention in fires has been described in different DGVMs in order to explore key factors that are missing or have rarely been treated or considered in DGVMs. This paper also investigates how human and human-related factors influence wildfires, by using examples from different parts of the world, including human behaviors, socioeconomic background, policy, laws and regulations, and cultural and traditional customs.

2. Categories of Human Impacts on Wildfires

Human impacts on wildfires can be divided into four categories: (i) human behavior and activities, (ii) socioeconomic factors, (iii) policies, laws, and regulations, and (iv) daily practice and traditional customs (Figure 2). These categories include effects that may increase or reduce the risk of fires, whereas some are contingent and depend on specific settings (Figure 3).

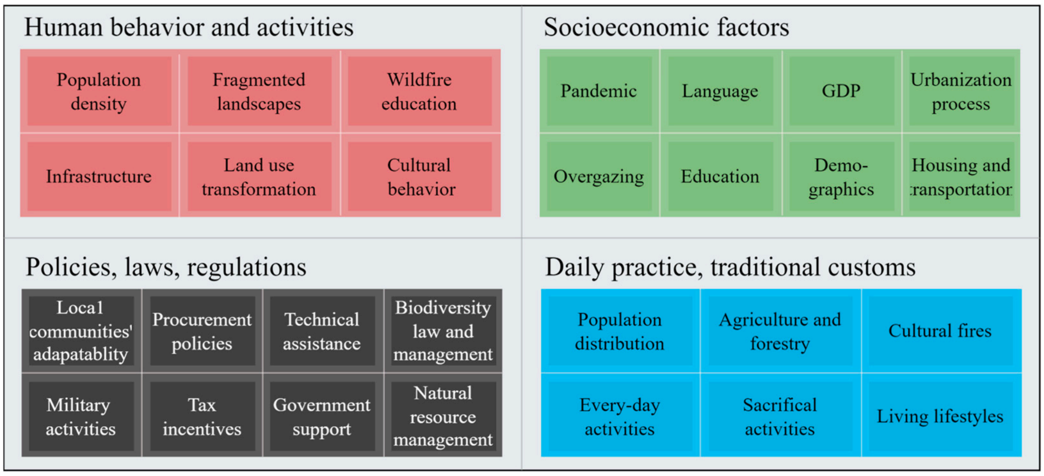

Figure 2. Categories of human impacts on wildfires.

2.1. Human Behavior and Activities

Human activities have shaped the complex nature of human-dominated landscapes and affect the distribution and intensity of wildfires [55]. For example, it has been shown that human ignitions, including arson, are the dominant sources of fire ignition in Europe, the U.S.; and South America [56–58].

Human behaviors can increase or reduce both fire risk and fire occurrence [59] (Figure 4). Fragmented landscapes and transformation of land use may, for example, reduce the fuel load and occurrence of large fires, while fire suppression and tree planting activities can increase fuel load and fire occurrence, especially in flammable ecosystems, which may lead to decline of biodiversity to some extent [60,61]. However, sometimes intended human ignitions are used to maintain or improve the biodiversity, since "fire storms" can be used to clear woody plants, e.g., in some grassland ecosystems in the U.S. and savanna areas in Southern Africa [62,63]. Similar schedules for prescribed fire burning, when temperature and soil moisture are beneficial, are also suggested for the Mediterranean area [64] and as a part of the Calluna heathland management along the Atlantic coast from Portugal to Norway [65].

Figure 3. Global examples of human activity and influence on wildfire ignition across the world, following the four categories from Figure 2, and color-coded according to the reported risk.

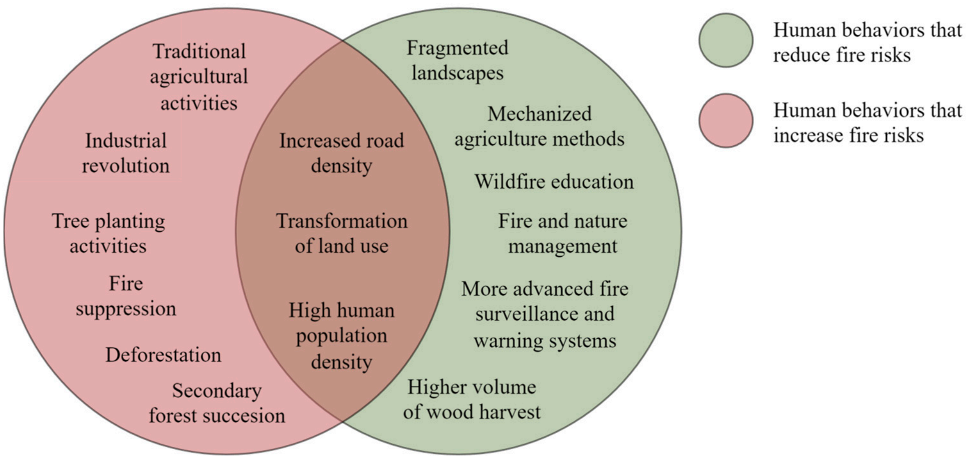

Figure 4. Examples of human-related factors that can either increase or reduce the risk of wildfires or even act in both ways depending on the varying local settings.

Although still debated, the industrial, agricultural, and technological revolutions, followed by a tremendous human population increase and loss of biodiversity, have probably moved our world into a new era, the Anthropocene [14,66]. This has greatly changed the way people use and cause fires. More fires occur when humans and human-related infrastructure extend to previously remote areas, and with more urbanization in the last decades, the WUI will increase in countries with expanding populations. Meanwhile, increased road density is likely to lower the area influenced by wildfires, as roads can act as fire barriers and increase the chances of fire suppression at initial stages. However, some argue that proximity to roads can be the main source of fire ignitions, because of added fuel load and continuity [67]. Also, the industrialization process may change the risk and occurrence of wildfires. Previous research has found that a higher volume of wood harvest can reduce fire occurrence by lifting the fuel load, and also higher livestock density may reduce the fire occurrence.

Human activities and agricultural land use in the urban–rural interface have been identified as key factors of wildfire occurrence [68]. It has also been argued that agricultural land use is crucial for understanding fires, since many fires in agricultural areas are intended for cultivation, clearing of land, or fertilization. However, global vegetation burning by traditional methods (e.g., slash-and-burn) has decreased after the development of more mechanized agriculture methods. Unfortunately, recent human land use has resulted in more frequent and severe fires, for example, deforestation in the Amazon region and land clearing in Indonesia, causing significant concern about the long-term impact on the high biodiversity within these regions.

Linear models show a positive correlation between population density and fire occurrence due to increased ignition sources, whereas nonlinear models reveal that fire occurrence may decline at very high densities. This is likely due to urbanization, reduced fuel continuity, and more effective fire suppression in densely populated areas. However, by using MODIS data to analyze fire ignitions in the western United States, it was found that human population density as such may not be a good indicator for predicting human ignition. Instead, more concrete human activities, for example how humans use the land, regional vegetation and ecosystems, surface fuel production, fuel fragmentation, and cultural behavior, could be taken into consideration.

The benefits of wildfire prevention and related educational activities have been documented to be higher than the costs. This indicates that establishment or improving of wildfire education is advantageous. Various stakeholders such as individuals and local communities can be involved in the fire prevention process, especially through knowledge transfer from education or practitioners.

Many people live in communities with a high risk of wildfires. One of the reasons is improper understanding of fire risk and pursuit of natural amenity in the WUI. Such communities may experience severe economic and social losses caused by wildfires. The so-called fire-adapted communities (FACs) in the United States reduce the fire risk by removing the fuel load around homes, providing support for collaborative wildfire planning, building fire breaks, introducing building demands for preventing fire damage, raising funds for fire suppression equipment, and raising people's awareness of fire control. While building FACs, various implementations may emerge in different contexts.

2.2. Socioeconomic Factors

To improve the understanding of the human drivers of wildfires, there is a great need for more contingent socioeconomic data [69]. For example, Gross Domestic Product (GDP) economic activity by area is significantly associated with burned areas. The lower the GDP, the bigger the burned area at the regional level.

Urbanization is also important, and one socioeconomic study of burned areas and fire occurrence in the Antalya forests in Turkey show that the percentage of people working in certain industries, unemployment rate, overall population, and illegal cutting are statistically important [70]. Another example from South Korea is that rapid urban expansion can result in increased fire occurrences [71].

Many studies have highlighted rural areas for understanding wildfire occurrence. Land abandonment in rural areas has resulted in added fuel load and increased seasonal fire occurrence in Portugal [72]. Similarly, in Madrid, Spain, the rural exodus and resulting rural land abandonment has led to land transformations into pastures and secondary succession with shrubs, which add fuel load that may cause serious fires. Likewise, agricultural land abandonment and expansion of mismanaged tree plantation are the main drivers of fire in the Mediterranean basin area. Studies have also reported that differences in fire regimes between Rif and Valencia in the Mediterranean basin can be connected to local socioeconomic factors, including the reduced rural population and overgrazing [73]. In addition, other socioeconomic factors including unemployment rates, the age of rural populations, customs of using fire in rural areas, and housing density should also be considered to identify the reasons for fire ignitions as well as for future fire prevention. A model that includes the value of WUI for analyzing global fire risk has been developed, describing potential damage to intact ecosystems of wildfires, finding that the most vulnerable areas and non-fire-adapted ecosystems are rainforests in the Amazon basin, Central Africa and Southeast Asia, the temperate forest of Europe, South America, and north-east America.

Socioeconomically disadvantaged communities may be more vulnerable to wildfires. Using census data and a vulnerability assessment framework, researchers have identified several key factors influencing a community's capacity to adapt to wildfire hazards, including demographics, housing and transportation, language and education, and socioeconomic status. Federal wildfire fuel projects in the U.S. favor more educated communities, and the unequal distribution of fuel management services may lead socioeconomically disadvantaged communities to be more vulnerable to wildfire hazards, including housing losses [74]. Taking two Australian states (New South Wales and Victoria) as examples, it has been argued that the relationship between wildfire hazard exposure and socioeconomic disadvantage is nonlinear, though the linkage between them is still positive and significant. One possible reason for heterogeneity of fire hazard exposure and socioeconomic background disadvantage is the lower availability of professional firefighters in rural areas. Likewise, an analysis of wildfire risk in Galicia, Spain, showed that socioeconomically disadvantaged communities are not likely to live in areas with a high share of WUI landscapes that are linked to a high wildfire risk, but because of weaknesses in education and the healthcare service, they may also be more vulnerable.

2.3. Policies, Laws, and Regulations

Local laws for preventing fires, for example in Switzerland and Italy, lead to decreased fire frequency, while the outcomes (e.g., burned area and fire occurrence) are more explicit when absolute fire bans and fire suppression work were enforced in high fire frequency areas [75,76] (Figure 5). Though strong fire suppression may reduce fires in the short term, the effect of fire suppression regimes over longer periods may be serious. For instance, the zero-fire suppression-oriented policy in the Brazilian Savanna area may increase fuel load and result in more serious fires later [77] (Figure 5). In addition, although wildfires in Mediterranean France have decreased sharply since 1994, due to the newly enforced fire prevention policy, a more comprehensive, balanced, and preventive-focused policy for fire suppression is needed to meet the emerging extreme weather conditions and changes in land use.

To understand wildfires in China, governmental policy should be a key factor. Because of governmental policy (Prevention and Suppression), people's awareness of fire safety has been raised on high temperature days, resulting in lower fire occurrence. In addition, the Chinese government's efforts in building green forest firebreaks can be seen as a useful tool to stop the spread of fire and enhance biodiversity management (Figure 5).

Biomass for energy production (e.g., forest plantations) is promoted in many countries (Figure 5). In western U.S. forests, state government support standards, tax incentives, technical assistance programs, and procurement policies to support biomass removal and renewal are implemented [78]. Similarly, forest extraction for bioenergy production is planned implemented across the Mediterranean area, which probably will contribute to reduced total burned area during extreme weather conditions [79].

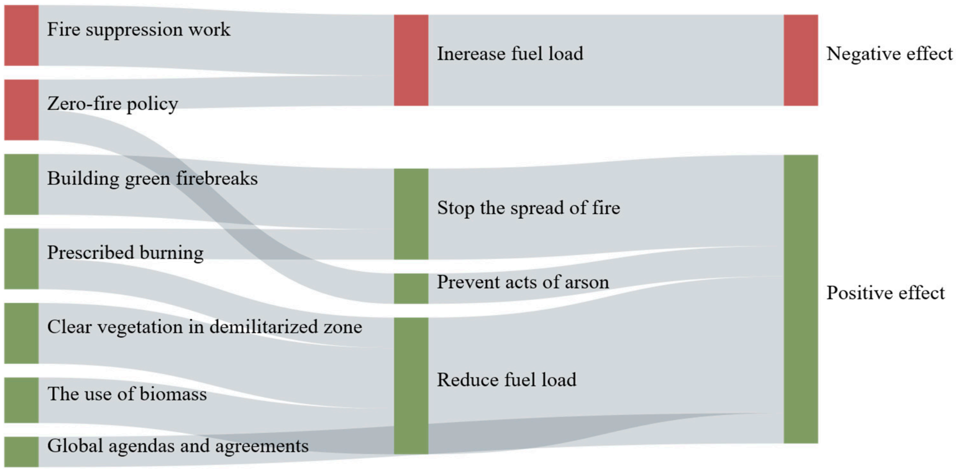

Figure 5. Potential influence of different policies, laws, and regulations on reducing fires.

Military activities can also influence regional fire regimes. For example, in the demilitarized zone between North Korea and South Korea (Figure 5), forests are cleared for increased visibility. Political system shifts may also influence fire regimes. For example, in Kazakhstan, many croplands were deserted after the collapse of the Soviet Union, and have since then been restored to steppe, which has increased the availability of fine fuels and consequently led to a higher risk of wildfires. [80].

Global agendas and agreements, including the United Nations Conventions on Biological Diversity and the Paris Agreement, have played an important role in the increased attention to fire regimes and its relevance to the environment (Figure 5). These agreements set global goals for biodiversity conservation and climate change mitigation, which in turn highlight the need to understand and manage fires as a key ecological process. Emerging availability of geospatial data will probably improve communities' adaptability to wildfires.

2.4. Daily Practice, Traditional Customs

Fire has been regarded as a sacred symbol in many cultures (Table 1), for example, in China and in other countries by Christians and the Jewish people [81]. In Eastern Poland, the All Souls' Day fire has been used to remember those who have passed away. Similarly, nowadays firewalking (pirovasiya) and some fire-related rituals and customs in Greece still exist, and during these events, there is a common belief that fire should be ignited by wood rather than using modern methods (e.g., firecrackers), which may trigger wildfires if it is not under careful usage [82]. In Britain, people also use fire during festivals. For example, in Shetland, people throw torches at ships during the fire festival of Up Helly Aa to mark Viking history [83]. During Bonfire Night, people also burn Guy Fawkes effigies to celebrate his failure in assassinating Protestant King James I [84].

In China, the Qingming Festival is also a day for remembering ancestors. Papers and firecrackers are usually burned near cemeteries, and wildfires sometimes unintentionally happen [85]. Although different fire regimes are claimed to be related to various customs of different villages, evidence is still lacking on the specific customs. Likewise, it is believed that cultural fires, which are linked with traditional holidays and rituals, has played a crucial role in fire regimes in northern China.

In South Korea, due to the shared Confucian culture, people also observe the tradition of using fire for remembrance rituals, and unintended ignition around grave lands was one of the main reasons for wildfires during 1960s and 1970s. However, this problem has declined since the 1970s, due to improvements and changes in funeral culture.

Table 1. Examples of fire-related culture and customs around the world.

Country/Region	Fire-Related Culture and Customs
China	Burning papers and firecrackers near cemetery on Qingming
	Lighting a giant torch at the Torch Festival among a few minorities
South Korea	Using fire for remembrance rituals
Britain	Burning Guy Fawkes effigies on Bonfire Night
	Throwing torches towards ships at Up Helly Aa
Poland	Lighting candles around graveyards on All Souls' Day
Greece and Bulgaria	Firewalking on Fire Festival
United States of America	Fireworks on Independence Day and New Year's Day
South America	Using fire for grazing and agricultural use
Brazil	The lifestyles of "queimada para limpeza," which means the cleaning fire
Indonesia	Using fire to clear farmland

Indigenous communities play an important role in shaping wildfire regimes in various regions through their cultural practices and traditional land management strategies. In South America, local people's culture and knowledge of fire have close associations with regional landscape management. Indigenous cultural and social systems influence local ecosystems through use of fire for grazing and agricultural improvements. These long-standing practices have contributed to shaping local ecosystems in sustainable ways. In Australia, instead of focusing solely on Indigenous lifestyles, researchers have emphasized the value of cross-cultural collaboration, suggesting that partnerships between Indigenous and non-Indigenous stakeholders may offer effective approaches to wildfire management.

In Southern African fires, population distribution and lifestyles has been found to influence human ignitions. Similarly, the lifestyles of "queimada para limpeza", which means the cleaning fire, can be used to understand frequent ignitions across various landscapes in Brazil, which may result in serious wildfires.

In Indonesia, people living in Kalimantan and Sumatra are still becoming accustomed to using fire to clear farmland, and it will be difficult for the Indonesian government to implement a zero-fire policy [86]. However, suppressing traditional use of fires, including prescribed fires, may hinder the process of controlling fires by using cost-effective ways to reduce fire risks.

3. Human Intervention in Fire-Enabled DGVM Models

In the previous sections we have assessed several human-related factors impacting wildfires. Before suggesting improvements in DGVMs, we here provide a brief survey of existing DGVMs including wildfire modules.

DGVMs are used in ESMs, which integrate human influences on wildfires through biophysical and behavioral drivers. They offer high-resolution representation of localized fire behavior (e.g., ignition likelihood near roads and WUI) and validation against satellite and historical fire data.

A wide variety of model structures and mechanisms have been designed and incorporated to model fires [87]. But in principle, the modeling of wildfires in DGVMs usually includes a fire ignitions module, a burning conditions module, and a fire growth module, which have been systematically described in the previous literature. In this work, we particularly focus on how human influence has been implemented in the existing fire-enabled DGVMs (Figure 6), which we summarized in Table 2.

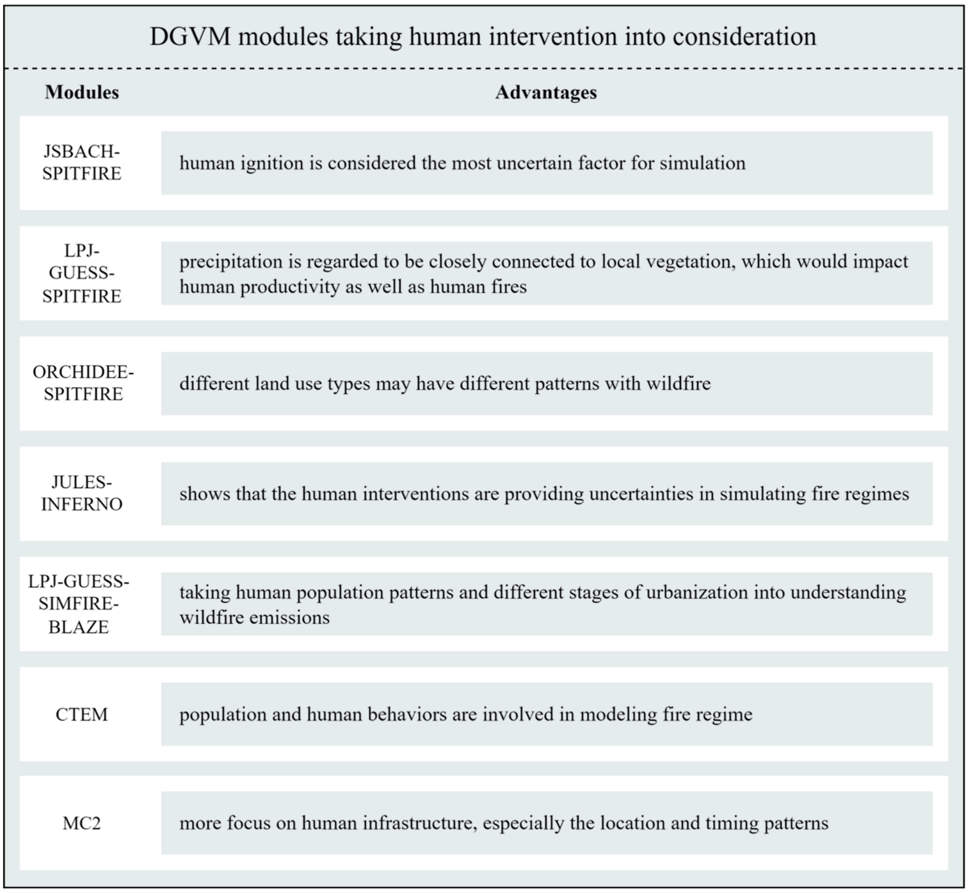

Figure 6. Main focus of human-related factors impacting wildfires in selected DGVMs.

Table 2. Specific human-related factors impacting wildfires implemented in selected DGVMs.

DGVMs	Human Ignitions	Fire Sup-Pression	Population Density	GDP	LULCC	Peak Month of Agri. Waste Burning
JSBACH-SPITFIRE	√					
ORCHIDEE-SPITFIRE	√		√			
LPJ-SPITFIRE			√			
LPJ-GUESS-SIMFIREBLAZE			√			
CLM-DGVM	√	√	√	√	√	√
JULESINFERNO			√			
CTEM	√	√	√			
MC2		√			√	

Population density has been the most commonly used factor in fire models. It has been widely used to define the fire ignition count both positively and negatively in the models. The positive effect (ignition) of population density is commonly implemented on an "effect per person" basis, used as a global constant in most models (e.g., CLM-Li, INFER-NO) [88]. Only a few models have implemented spatial variation in this parameter, such as JASBACH-SPITFIRE and LPJ-GUESS-SPITFIRE [89]. The negative (suppression) effect of population density on the fire ignition count has been taken into account either explicitly (e.g., CLM-Li) or implicitly through various parameterizations of "effect per person" (e.g., JASBACH-SPITFIRE, such as the suppression of burned area per fire (e.g., CLM-Li) or the reduction in the duration of each fire event (e.g., JSBACH-SPITFIRE) in some of the models.

GDP, as a proxy for socioeconomic conditions, has been employed in some DGVMs, such as CLM-Li [90], to describe the impact of socioeconomic conditions on fires, particularly the suppression of burned area per fire. In addition, the influence of land use and land cover (e.g., crop fraction) on wildfires, has also been implemented in a few DGVMs (e.g., LPJ-LMfire, ORCHIDEE).

Overall, although existing DGVMs have included human interventions, human activities and socioeconomic factors have been limited to population density, GDP, and land use types (e.g., crop fraction), for which global gridded data are readily available. Human activities for actively preventing fires, such as fire prevention policies, fire management practices, use of advanced technology and trained antifire forces for monitoring and depressing fires, and improvement in people's awareness of using fire safely in the local community are still lacking, largely due to difficulties in quantifying such measures at global scales. These factors may be incorporated into future work using proxy indicators, expert-based scoring systems, or regional policy indices as qualitative or semi-quantitative variables. Common or divergent responses across the models to some human factors have been noticed. For instance, all models underpredict wildfires at low road density, while different models show divergent response to cropland fraction [91].

4. Further Suggestions for Developing DGVMs

Earth System Models (ESMs) and Integrated Assessment Models (IAMs) serve distinct but complementary roles in analyzing human–Earth system interactions. ESMs simulate physical and biogeochemical processes (e.g., atmospheric circulation, ocean dynamics, carbon cycles) with high spatial and temporal resolution. They use detailed, process-based equations to model Earth system feedback, often requiring supercomputers. An important purpose of ESMs is to simulate long-term climate changes under various emission scenarios. IAMs, on the other hand, focus on socioeconomic systems (e.g., energy, land use, economics) coupled with simplified climate components to evaluate policy impacts. They rely on reduced-complexity climate representations to prioritize economic and policy analysis. Their main use is assessment of mitigation pathways, cost–benefit analyses, and technology transitions. Human-related wildfires are normally addressed differently in ESMs and IAMs, reflecting their distinct focuses and methodologies. We here argue that parametrizations and lessons learned using IAMs can help further develop DGVMs for use in ESMs.

4.1. Refining the Relationship Between Human Factors and Wildfires in Current Parametrizations

However, let us first address, as an obvious starting point, current implementations of human factors on fires in DGVMs currently used in global studies coupled to ESMs. DGVMs are strongly limited by the availability of global spatial gridded data. So far, population density, GDP, and land use types remain the most accessible dataset for such purposes. The impact of these parameters on fire count and burning area through both ignition and suppression, however, has been implemented in DGVMs in a heuristic way and usually oversimplified with constant global parameters. This has been recognized as the most uncertain area for fire simulations in DGVMs [92]. Recent studies have emphasized the complexity and regional variability of human–fire interactions [93,94], pointing to the necessity of applying region-specific parameters and even parametrizations in DGVMs. Other human-driven factors—such as the use of advanced decision support tools by fire managers, institutional response capacity, and local fire governance—may also significantly shape fire outcomes and should be considered in future model development. As availability and accuracy of global fire datasets increase, using Machine Learning (ML) and other Artificial Intelligence (AI) approaches instead of simple statistical equations to derive a more sophisticated and accurate formulation between human factors and wildfires for DGVMs become a more and more viable and promising approach.

4.2. Adding New Human Factors to DGVMs

As discussed in Section 2, there is a wealth of human impacts on wildfires, which we categorized as human behavior and activities, socioeconomic factors, policies, laws, and regulations, as well as daily practice and traditional customs (Figure 2). Admittedly, the human factors (e.g., population density, GDP) used in DGVMs to influence wildfires are mostly heuristic and indirect. The employment of human factors (e.g., number of fire-fighters and location, fire policies in different provinces or counties etc.) that can more directly influence fires will be beneficial for more accurate fire simulation in DGVMs. These data may be hard to obtain globally, but the availability of such data can be high on a regional or national level. For instance, on a regional or national level, the spatial resolution of land cover use data can usually reach meter-scale, allowing a better depiction of the barriers to fire (e.g., roads, firebreaks), which can be directly used in DGVMs. DGVMs can readily be applied at the regional scale, although they were been originally designed for global simulations. Therefore, when regional human factor data are available, developing region- or nation-specific fire schemes using more directly human factors in DGVMs can be a good choice.

As vegetation demographics have been more commonly incorporated into DGVMs [95] in recent years, this opens up more possibilities to represent human intervention in fire in DGVMs. For instance, fire management involving cutting different sizes/ages of trees to reduce fire risks can be better represented in such models. More research and development of this new avenue remain to be explored.

4.3. Towards Integration with IAMs

Many aspects of human impacts on wildfires are far better described in IAMs, which are of paramount importance in advancing our understanding of the coupled human–Earth system. IAMs directly link wildfires to policy decisions (e.g., carbon pricing, urban planning), and they are flexible for exploring socioeconomic uncertainties (e.g., population growth, technological adoption). Therefore, they offer a powerful framework for capturing the complex interactions between human activities and environmental changes, enabling a comprehensive understanding of the region's impacts on biodiversity, ecosystem services, and the carbon cycle. Thus, they are particularly strong in their treatment of socioeconomic factors, and of policies, laws, and regulations, two of the categories we established in Section 2 (Figure 2).

DGVMs or similar models have been widely integrated into various IAMs to better understand the interactions between land-based socioeconomic aspects, such as energy, materials, land use, and climate systems. By linking the human dimensions of wildfires in DGVMs with those in IAMs, we will be able to better understand the intricate political–socioeconomical feedback of human interventions and wildfire dynamics. This integration allows for the consideration of cultural, societal, and organizational factors that influence fire regimes. Moreover, it facilitates a more holistic representation of the coupled human–Earth system within the DGVM–IAM framework, enabling us to account for policy changes, world events, and dynamic fire regimes. So far, there are few IAM studies considering the relationship between human society and wildfires, and few studies on DGVMs on coupling fire dynamics with IAMs. This highlights the urgent need to work towards this direction.

These advancements in DGVMs, informed by both scientific and technological considerations and human, cultural, and organizational factors provided by IAMs, can lead to a more accurate assessment of future fire scenarios, which can feed back to IAMs for socioeconomic adaptations. They provide a foundation for making informed policy decisions and developing sustainable wildfire management strategies in the future to minimize fire risks/damage while maximizing ecological benefits. Integrating these factors within the DGVM–IAM framework ensures a more comprehensive modeling approach that captures the real-world complexities associated with human intervention and wildfire dynamics [96,97].

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