THE UNIVERSITY OF CHICAGO | EXISTENTIAL RISK LABORATORY

A REPORT ON ASSUMPTIONS AND UNCERTAINTIES IN MODELING NUCLEAR WINTER

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Abstract. A nuclear winter would be, for lack of better words, really bad. Much of the modeling and research that exists on nuclear winter relies on several outdated assumptions or has been altered to elicit a specific political response, thus exaggerating or downplaying the severity. The nuclear field often conflates the 'politically irrelevant' with the 'scientifically resolved.' When certain questions fall out of political relevance, the field most often stops investigating them and considers them solved.

Over time, the nuclear field has become narrowly focused on preventing nuclear war, and because of this it has largely failed to rigorously re-examine and update the scientific foundations of our understanding of how a nuclear winter occurs and behaves. This report interrogates current nuclear winter models, relevant literature, and prevalent scientific research to more clearly identify and understand the assumptions and uncertainties that underpin the field's understanding of nuclear winter.

The broader goal is to identify assumptions in the literature and evaluate how strongly each assumption is supported. In identifying these assumptions and uncertainties throughout the different phases of the nuclear winter mechanism chain, we both replicated methodologies from past models and developed new methodologies and conclusions to determine the validity of the assumptions themselves. Informed by this research, we developed a more comprehensive research agenda on where the field's understanding of nuclear winter falls flat, and how more recent and multidisciplinary research can bolster analysis more broadly.

1. Introduction

Nuclear winter is the biggest consequence of a nuclear war that the nuclear risk field seeks to prevent. Experts study nuclear winter in order to prevent civilizational collapse and widespread catastrophe. The winter effect occurs when mass firestorms from nuclear detonations inject soot into the lower stratosphere where it can remain for extended periods of time, blocking sunlight from reaching the Earth's surface; essentially an "anti-greenhouse effect." This phenomenon would trigger surface temperature drops of 16°F or more, agricultural system collapse, widespread global famine, and ozone layer destruction capable of causing widespread environmental damage and health concerns. And contrary to conventional understanding, a nuclear winter can be triggered from even a regional or limited nuclear exchange, for example, between India and Pakistan.[1] For lack of better words, a nuclear winter would be really *really* bad for everyone.

As long as the risk of nuclear war exists, so too will the catastrophic risk of a nuclear winter. Despite this, interest and research in modeling the effects of nuclear winter have waned since the 1990s. This has caused much of nuclear winter research and modeling to rely on several outdated assumptions, or be altered to elicit a specific political response, thus exaggerating or downplaying the severity of a nuclear winter. During the height of the Cold War, when nuclear risk was perceived as being at an "all time high," political will played a key role in galvanizing academic and scientific interest in studying nuclear winter and its effects.[2] This dynamic also affected how the civilian public perceived the risk of nuclear winter as it was communicated to them. The nuclear field often conflates the 'politically irrelevant' with the 'scientifically resolved.' When certain questions fall out of political relevance, the field most often stops investigating them and considers them solved. Over time, the nuclear field has become more narrowly focused on preventing nuclear war, and because of this the field has largely failed to more rigorously re-interrogate and update the scientific and epistemological foundations that form our understanding of nuclear winter.

Nuclear winter research has evolved significantly since the 1980s, when nuclear winter began to garner scientific inquiry. The foundational work on nuclear winter, particularly the 1983 and later 1990 TTAPS studies (Turco, Toon, Ackerman, Pollack, and Sagan) and the public facing companion, Sagan and Turco's *A Path Where No Man Thought* (1990), established the basic physics of how nuclear detonations could trigger catastrophic climate effects.[3] Beyond estimates and models, Sagan and Turco also discussed the broader moral imperative scientists at the time felt to mitigate the risk of nuclear war because it could lead to civilizational collapse from the effects of nuclear winter.[4] In 1977, Glasstone and Dolan published the third edition of *The Effects of Nuclear War,* a study that despite being over 50 years old, is still frequently cited and is considered the "gold standard" in the nuclear field.

These early models were developed during the latter half of the Cold War and were explicitly tied to both political agendas and policy objectives. This was a key factor in shifting public perception of

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[1] Owen Brian Toon et al., "Atmospheric Effects and Societal Consequences of Regional Scale Nuclear Conflicts and Acts of Individual Nuclear Terrorism," Atmospheric Chemistry and Physics 7, no. 8 (April 2007): 1973–2002.

[2] William Burr, "Nuclear Winter: U.S. Government Thinking During the 1980s," Document 9, The National Security Archives, October 30, 2024, https://nsarchive.gwu.edu/briefing-book/climate-change-transparency-project-nuclear-vault/2022-06-02/nuclear-winter-us.

[3] R. P. Turco et al., "Nuclear Winter: Global Consequences of Multiple Nuclear Explosions," Science 222, no. 4630 (December 23, 1983): 1283–1292.

[4] Carl Sagan and Richard P. Turco, A Path Where No Man Thought: Nuclear Winter and the End of the Arms Race (New York: Random House, 1990).

nuclear war from a bilateral conflict between nations to an existential threat to humanity itself. From 1993 to around 2007 there was a distinct absence of nuclear winter modeling, as in the immediate post-war period, the primary threat was dissolved, and nuclear risk seemed to be less of a priority amidst progress to stockpile reductions after the war, and increased prevalence of both democratization and diplomacy. Moreover, funding dried up, and scientific interest shifted to other topics.

Although climatologist Alan Robock began studying nuclear winter in the 1980s, Robock and a number of other colleagues including Michael J. Mills, Owen B. Toon and Richard P. Turco began publishing updated nuclear winter models in the mid 2000s and onwards. Robock et al. and his datasets are largely dominant in the literature. Despite the resurgence of modeling in the 2000s, the field has struggled to achieve a truly modern synthesis. Recent research efforts, most notably the 2025 National Academies of Science Engineering and Medicine (NASEM) study on the effects of nuclear war, underscore a growing tension within the research and policy community. Congressionally mandated and published in June 2025, the NASEM report represents the first comprehensive federal assessment of nuclear winter since 1985 and was led by a broader committee of relevant experts. The study aimed to evaluate potential environmental, social, and economic effects that could unfold over weeks to decades following a nuclear war, drawing on advancements in Earth systems modeling and climate science that have emerged over the past four decades.

The National Academies' findings reveal both progress and persistent limitations in the field but fail to provide actionable solutions to addressing key uncertainties. Instead, the study points out knowledge gaps while leaving them unsolved. More broadly, experts criticized the report's modeling uncertainties; the report committee identified serious uncertainties in "the time-varying parameters of the fire, such as the fire size and geometry, fluxes of heat, moisture, and emissions, and aerosol transport."[5] Without adequate analysis in these areas, it is nearly impossible to assert reputable conclusions on soot injection and thus, climatic effects. On the topic of soot injection, the NASEM study's conclusions are overly conservative, likely because the study largely relied on Los Alamos National Lab researcher Jon M. Reisner's research on pyroCb events and fire modeling (Reisner was also a committee member on the study). Reisner et al. (2018) concluded: "while our thorough simulations of the firestorm produce about 3.7 × 109 kg of black carbon, we find that the vast majority of the black carbon never reaches an altitude above weather systems. Therefore, our Earth system model simulations conducted with model-informed atmospheric distributions of black carbon produce significantly lower global climatic impacts than assessed in prior studies, as the carbon at lower altitudes is more quickly removed from the atmosphere."[6] Reisner et al. (2018) identified key uncertainties, but the estimates led to push back from Robock, Toon, and Bardeen: they argued that Reisner et al.'s fire models didn't adequately capture pyro-convective dynamics and latent heating effects that enable stratospheric injection.[7] The discussion on plume height, injection, and firestorm dynamics is still ongoing.

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[5] National Academies of Sciences, Engineering, and Medicine, Potential Environmental Effects of Nuclear War (Washington, DC: The National Academies Press, June 2025), https://www.nationalacademies.org/news/potential-environmental-effects-of-nuclear-war-new-report.

[6] Jon M. Reisner et al., "Climate Impact of a Regional Nuclear Weapons Exchange: An Improved Assessment Based on Detailed Source Calculations," Journal of Geophysical Research: Atmospheres 123, no. 5 (February 2018), https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2017JD027331.

[7] Alan Robock, Owen B. Toon, and Charles G. Bardeen, "Comment on 'Climate Impact of a Regional Nuclear Weapon Exchange: An Improved Assessment Based on Detailed Source Calculations' by Reisner et al.," Journal of Geophysical Research: Atmospheres 124, no. 20 (October 19, 2019), https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JD030777.

A 2022 paper from Tarshish and Romps on the vital role of latent heating for a firestorm to achieve stratospheric penetration also supports Robock and Toon's research.[8] Robock was also on the NASEM study's committee. This debate highlights that while the NASEM study did not downplay the severity of a regional or limited conflict, it did understate the effects and did not resolve any key uncertainties on soot injection. Moreover, this demonstrates a broader lack of serious engagement in the report with more recent literature on the global effects of nuclear winter including: Xia et al. (2022) on 5 billion deaths from nuclear famine; minimal mention of Bardeen et al. (2021), and research on ozone depletion work; limited treatment of ocean circulation changes from the Coupe et al. (2021) nuclear niño study; and little discussion on UV radiation increases post-nuclear war. The study also mentions that it does not consider residual radiation, which in many cases, plays a role in the longer-term effects of a nuclear winter.[9]

The NASEM report also emphasized throughout its 235 pages that more research needs to be done due to "key uncertainties and data needs."[10] The committee identified substantial variability in potential estimates depending on factors including weapon yields, number of cities targeted, flammable material content, firestorm duration, and atmospheric conditions. Despite its imperfections, studies like the NASEM report are vital, as they indicate both policy relevance and robust government interest in understanding the effects of nuclear war. Overall, the NASEM study thus validates the core premise that a large or limited nuclear war could produce severe climate disruption while simultaneously revealing how much remains uncertain about the magnitude, duration, and regional distribution of these effects. This ambiguity has significant policy implications: if models overstate the severity of nuclear winter, they risk losing credibility and undermining arms control efforts; if they understate it, policymakers and military strategists may systematically underestimate the overall civilizational risk of a nuclear conflict. The report's emphasis on uncertainty reflects an honest scientific assessment, though it also highlights the field's ongoing struggle to move beyond decades-old assumptions in an era focused primarily on prevention.

The evolution from the foundational TTAPS model to the Robock era, and to increased government interest, represents a significant increase in computational and analytical capabilities, yet the underlying physical assumptions have remained strikingly stuck in the past. In many of these studies, experts have been running 21st century advanced atmospheric simulations on 1960s urban sociology— before the widespread use of plastics, before modern high-rise construction standards, and before the data revolution that gave experts access to high-resolution satellite imagery, real-time atmospheric monitoring, machine learning, and reproducible global datasets. The field has access to and utilizes advanced climate models from one-dimensional radiative-convective approximations to fully coupled Earth system models with interactive ocean, land, sea, ice, and atmospheric chemistry. Yet the inputs to these sophisticated models, including fuel loads, firestorm formation, soot production estimates, and injection heights, still rest heavily on observations from Hiroshima in 1945.

As a result of the failure to integrate critical shifts in technology, material science, urban density, and data access, the field remains trapped in an epistemological loop where "new" nuclear winter models often merely reaffirm old uncertainties with greater computational precision. The 2025 NASEM

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[8] Nathaniel Tarshish and David M. Romps, "Latent Heating Is Required for Firestorm Plumes to Reach the Stratosphere," Journal of Geophysical Research: Atmospheres 127, no. 16 (August 2022), https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022JD036667.

[9] National Academies of Sciences, Engineering, and Medicine, Potential Environmental Effects of Nuclear War (Washington, DC: The National Academies Press, June 2025).

[10] *Ibid.*

study's call for improved understanding of the physical effects of nuclear weapons, and the assessment of civilizational/political consequences echoes concerns raised in the 1985 National Research Council (NRC) report on the atmospheric effects of a major nuclear exchange.[11] This suggests that four decades of modeling advances have not fundamentally resolved any of the core uncertainties about how nuclear winter would likely unfold.

This research seeks to break this feedback loop. By systematically reevaluating each stage of the nuclear winter mechanism chain with modern datasets, machine learning, and open-source computational tools, we provide a more rigorous and transparent update to these foundational assumptions and uncertainties. Our research demonstrates that the tools to update our assumptions already exist (e.g., satellite remote sensing, global land cover classification data, combustible material datasets, material intensity databases, and advanced fire behavior models from wildfire research) but simply have not yet been applied to nuclear winter scenarios. In doing so, we hope to provide robust analysis that shifts the field's conversations on nuclear winter, from reaffirming historical estimates to actively interrogating them, and to develop a novel research agenda that identifies key areas and questions where more research is necessary. If the goal remains to prevent nuclear war, the field must ensure that our science on nuclear winter reflects modern capabilities and scientific knowledge, rather than how it existed in 1945 or 1977.

2. Methodology

The project's methodology directly addresses two fundamental problems that have plagued nuclear winter research for decades: the "black box problem" and the "Hiroshima proxy." Understanding these problems is vital to appreciating why our approach represents a meaningful departure from previous literature on nuclear winter. Most nuclear winter models treat the key stages of the mechanism chain as "black boxes." In other words, stages with complex non-generalizable physical processes are replaced by simplified assumptions or empirical relationships derived from limited historical and scientific data. The firestorm formation stage illustrates this problem most clearly: conventional treatment of firestorms assumes that any weapon with sufficient yield and fuel density detonated over a city will automatically produce a self-sustaining firestorm capable of lofting soot into the lower stratosphere. This assumption conflates correlation with causation: because Hiroshima's 15-kiloton airburst triggered a firestorm of a defined radius that (presumably) injected soot into the stratosphere, the relationship is treated as deterministic and generalizable. Much of the complex physics that connect individual ignitions to a soot-lofting convective column are glossed over or are absent entirely.

The black box treatment of nuclear winter has serious policy implications. If models systematically overestimate the likelihood or intensity of firestorm formation, they may predict catastrophic nuclear winter scenarios for conflicts that would produce severe but regionally contained effects. Conversely, if models fail to account for how modern urban materials like plastic burn differently than wood, they may underestimate soot production and injection efficiency. Either could lead to even more flawed assumptions that become solidified in doctrine and arms control negotiations and broadly inform the risk of nuclear war itself.

The Hiroshima proxy represents a specific manifestation of the black box problem that has become so deeply embedded in nuclear winter literature that it functions as unquestioned doctrine. The

[11] National Research Council, The Effects on the Atmosphere of a Major Nuclear Exchange (Washington, DC: National Academies Press, 1985), https://www.nationalacademies.org/publications/540.

15-kiloton bomb dropped ~600 feet above Hiroshima ignited fires across a roughly 13 km^2 area, and those fires merged into one mass fire that burned for several hours. Hiroshima is the only instance of nuclear use that directly caused a firestorm in human history and has been used to extrapolate how nuclear weapons would behave in modern exchanges with more destructive and capable weapons. Glasstone and Dolan (1977) codified this relationship, establishing that materials exposed to thermal fluence above approximately 10 cal/cm^2 will ignite.[12] As this report will discuss in the following sections, the Hiroshima proxy has become a circular reference: we use Hiroshima for scaling to today's weapons to predict nuclear winter but we don't actually know what Hiroshima's atmospheric effects looked like, as it occurred before modern atmospheric monitoring existed.

Our research systematically opens these black boxes by decomposing the nuclear winter mechanism chain into discrete, physically grounded stages and interrogating the assumptions at each stage using modern datasets, recent scholarship, and computational tools. Rather than accepting the Hiroshima proxy as doctrine, we ask: what would actually happen if a nuclear weapon detonated over a modern sprawling city given current understanding of urban fuel loads, fire behavior, atmospheric dynamics, and soot injection? Additionally, our research leverages several datasets and tools that either did not exist or were not publicly available when foundational nuclear winter studies were conducted. Thus, we structure our methodology and analysis around the five stages of the nuclear mechanism chain. Our understanding of each stage drastically impacts each subsequent stage, as well as final estimates and analysis.

3. Assumptions and Uncertainties

This section establishes the central assumptions and uncertainties present in research on each stage of the mechanism chain, and summarizes the research and analysis completed to address them. The following sections cover thermal ignition, firestorm formation and the basics that inform soot injection, modern fuel load estimates, the nature of combustible material and land classification, and target list development. Understanding the stages that precede soot injection and global circulation, as well as correcting their assumptions, is crucial for producing more accurate estimates and analysis on the later stages. Thus, an area for future research is focusing on soot injection and global circulation, and this will be discussed in the research agenda section of this report.

3.1 Thermal Ignition

Thermal ignition is the process by which a nuclear detonation's thermal pulse ignites combustible materials in the surrounding target area.[13] Thermal ignition is also the first step in the nuclear winter mechanism chain. In context of thermal ignition, it is important to differentiate between certain terms: thermal fluence refers to the amount of radiant energy delivered per unit area (cal/cm^2), and the ignition radius refers to the maximum distance from ground zero where thermal fluence is still high enough to ignite combustible materials.[14]

[12] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons (Washington, DC: U.S. Department of Defense, Energy Research and Development Administration, 1977), https://fissilematerials.org/library/gla77.pdf.
[13] Harold L. Brode, "Thermal Radiation from Nuclear Explosions," Report, RAND Corporation, August 1963, https://www.rand.org/content/dam/rand/pubs/papers/2008/P2745.pdf.
[14] A. M. Kanury, "Considerations in Scale-Modeling of Large Urban Fires," Defense Nuclear Agency, November 1984, https://apps.dtic.mil/sti/tr/pdf/ADA168497.pdf.

Glasstone and Dolan's *The Effects of Nuclear Weapons* (1977) provides the quantitative foundation for ignition thresholds, establishing that materials exposed to thermal fluence above approximately 10 cal/cm^2 will ignite.[15] Glasstone and Dolan (1977) assert that for a 15 kiloton airburst (similar to Hiroshima) the ignition threshold is reached within a radius of approximately 2.03 kilometers, which corresponds to an ignition area of approximately 13 km^2. It is important to note that determining the effective size of the target area is not a matter of arbitrary geographic selection, but of defining a zone based on physical thresholds. These physical thresholds determine where ignition can actually occur. Understanding the energy release in a nuclear detonation is also necessary for calculating the ignition radius. The energy in a nuclear blast is divided into three kinds: 50% blast; 35% thermal radiation; and 15% nuclear radiation.[16] This led us to demonstrate what is referred to as a "tile" area: a well-defined zone determined by two co-dependent variables— a minimum thermal fluence threshold, and minimum combustible fuel load. Essentially, the tile represents an area where both of these conditions for ignition and sustained combustion are met. The following equation provides the physical basis for this relationship in Glasstone and Dolan (1977):

$$Q = fY\tau \;/\; 4\pi^2$$

Where Q is thermal fluence or ignition threshold (10 cal/cm^2), f is the fraction of explosion considered thermal energy (0.35), Y is total energy and yield converted to calories (i.e., 15 kt x 10^{12}), τ is the atmospheric transmission factor (assumed to be 1.0 with clear visibility), and r is the distance or radius from the detonation center (2.03 km), it follows that,[17]

$$\textit{Solve for } r = r = \sqrt{}\, fY\tau \;/\; 4\pi Q$$

$$r^2 = (15 \times 10^{12})\ 0.35 \;/\; 4\pi \times 10$$
$$r^2 = 5.25 \text{ x } 10^{12} \;/\; 4\pi \times 10$$
$$r^2 \approx 5.25 \text{ x } 10^{12} \;/\; 125.66 \text{ cm}$$
$$r^2 \approx 4.177 \text{ x } 10^{10} \text{ cm}^2$$
$$r \approx 204397 \text{ cm} \approx 2.03 \text{ km}$$

$$\text{Ignition "tile" area} \approx \pi\,(2.03 \text{ km})^{\,2} \approx 12.9 \text{ km}^2$$

This relationship between yield, thermal fluence, and ignition area formed the physical basis for what is known as the "Hiroshima proxy." Toon et al. (2008) discussed this expression: "In particular, since the area within a given thermal energy flux contour varies linearly with yield for small yields, we assume linear scaling for the burned area."[18] Glasstone and Dolan (1977) also assumed linear interpolation between appropriate curves, for yields other than those shown in figures.[19] This singular

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[15] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons (Washington, DC: U.S. Department of Defense, Energy Research and Development Administration, 1977).

[16] Jack C. Rogers and T. Miller, "Survey of the Thermal Threat of Nuclear Weapons," Clearinghouse, U.S. Department of Commerce for the Office of Civil Defense, July 1964, https://apps.dtic.mil/sti/tr/pdf/ADA383988.pdf.

[17] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons (Washington, DC: U.S. Department of Defense, Energy Research and Development Administration, 1977).

[18] Owen B. Toon et al., "Environmental Consequences of Nuclear War," Physics Today 61, no. 12 (December 2008): 37–42.

[19] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons (Washington, DC: U.S. Department of Defense, Energy Research and Development Administration, 1977).

data point from the only historical instance of nuclear use that triggered a firestorm (Nagasaki did not) essentially became doctrine in the field, and was assumed to linearly scale to more destructive, compact, and precise weapons of different yields; the field makes a leap, assuming that ignition area is proportional to weapon yield (linear, via square root scaling of radius). Hiroshima is the historical anchor for this relationship, although that scaling hides several nonlinear dependencies. This figure has become standard in the literature, and in canonical nuclear winter research.

While Glasstone and Dolan (1977) define this relationship as static, more recent literature on nuclear winter and related effects, including Lundquist, et al. (2020), critique this and instead defines and visualizes the relationship in terms of dynamic fuel-load modeling and non-linear atmospheric interactions. One of the Lundquist, et al. (2020) study's key differences was that it "examined the dependence of the climate effects on different amounts of fuel available at the location of the detonation and subsequent fire."[20] By considering a range of possibilities for fuel loading at the site of the fire and plume characteristics, such as smoke composition and aerosol properties, the study resulted in an improved understanding of model sensitivity to these factors.[21] The inclusion of these factors and their results demonstrate a structured critique of the Hiroshima proxy's linear scaling assumption. Additionally, the 2025 National Academies report also identified fire ignition and fuel mapping as one of the biggest uncertainties in current models yet did little to advance the field's understanding.[22]

Critiquing the proxy's assumptions involves reconceptualizing thermal ignition from a geometric and deterministic energy distribution (i.e., a focus solely on spatial layout), to a stochastic environmental model, which better accounts for uncertainty and unpredictable factors.[23] Most climate models produce accurate results when measuring effects over a long period of time (e.g., climate change) but some models struggle with sudden and unpredictable atmospheric changes.[24] It is not purely physics anymore; advancements in modeling and technology can better help us understand atmospheric dynamics, and how they play out through soot injection. Thermal ignition is highly dependent on both the environment and the physical infrastructure that surrounds the detonation target area. Moreover, there are four fundamental flaws in the Hiroshima Proxy's linear assumption: topographical and meteorological stochasticity; variable atmospheric transmittance; fuel density and urban geometry; and lastly, pulse duration and thermal inertia.

Glasstone and Dolan's linear scaling assumption treats the Earth's surface as uniform, where in reality terrain, altitude, and weather vary dramatically, especially in modern environments. Hiroshima in the 1940s was relatively flat, with mostly two-story buildings constructed from wood; modern strategic urban targets like Chicago, Denver, and Los Angeles have much more complex topography that would create highly irregular ignition patterns. Terrain shadowing in modern urban environments is also a factor, where hills, valleys, highway systems, and tall buildings create thermal shadows where fluence drops below Glasstone and Dolan's 10 cal/cm^2 threshold, even within the calculated ignition

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[20] Stephen Wampler, "Examining Climate Effects of Regional Nuclear Exchange," Lawrence Livermore National Laboratory, November 30, 2020, https://www.llnl.gov/article/46991/examining-climate-effects-regional-nuclear-exchange.
[21] *Ibid.*
[22] National Academies of Sciences, Engineering, and Medicine, Potential Environmental Effects of Nuclear War (Washington, DC: The National Academies Press, June 2025).
[23] Peter Reichert, et al. "Potential and Challenges of Investigating Intrinsic Uncertainty of Hydrological Models with Stochastic, Time-Dependent Parameters," Water Resources Research, Volume 57, Issue 3, March 2021. agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020WR028400
[24] "Basics of Global Climate Models," U.S. Department of Agriculture, USDA Northwest Climate Hub, 2026, https://climatehubs.usda.gov/hubs/northwest/topic/basics-global-climate-models.

radius.[25] Urban areas can also produce heat islands. The more recent Reisner et al. (2018) study takes topographic considerations into account in fire modeling. Additionally, some geographic areas possess microclimates, where the meteorological conditions can change dramatically between relatively short distances.[26] For example, in Monterey California it could be 60°F and rainy while just a few miles away, Carmel Valley could be sunny and 70°F. These pre-existing temperature gradients likely affect ignition probability. Meteorological conditions like high humidity, precipitation, fog, and cloud cover all affect atmospheric transmittance, in addition to what can or will be ignited.

The Earth's atmosphere is composed of numerous gases and aerosols; these constituents both absorb and scatter radiation as it travels from the target to the thermal imaging system.[27] Atmospheric transmittance is this fraction of radiation (e.g., sunlight) that passes through the atmosphere without being absorbed or scattered by these gases and aerosols. Glasstone and Dolan (1977) acknowledge that atmospheric transmittance (τ) varies, but assume it is equal to 1.0 for their calculations.[28] Real world conditions, including visibility will always vary and can greatly affect thermal ignition, and the ignition radius: Glasstone and Dolan provide the following transmission factor values ranging from $\tau \approx 0.9$ for clear conditions to $\tau \approx 0.3$ for heavy fog or rain (figure 7.42). Applying these values to the ignition radius equation reveals dramatic variation in predicted ignition area:

Excellent Visibility (Clear Day)	Moderate Visibility (Hazy)	Poor Visibility (Fog or Rain)[29]
Where $\tau \approx 0.9$ $r = \sqrt{fY\tau / 4\pi Q}$ $r = \sqrt{(0.35 \times 15 \times 10^{12} \times 0.9 / 4\pi \times 10)}$ $r \approx 1.94$ km Area = $\pi (1.94)^2 \approx 11.8$ km^2	Where $\tau \approx 0.6$ $r = \sqrt{fY\tau / 4\pi Q}$ $r = \sqrt{(0.35 \times 15 \times 10^{12} \times 0.6 / 4\pi \times 10)}$ $r \approx 1.58$ km Area = $\pi (1.58)^2 \approx 7.8$ km^2	Where $\tau \approx 0.3$ $r = \sqrt{fY\tau / 4\pi Q}$ $r = \sqrt{(0.35 \times 15 \times 10^{12} \times 0.3 / 4\pi \times 10)}$ $r \approx 1.12$ km Area = $\pi (1.12)^2 \approx 3.9$ km^2

While these calculations provide a 67% reduction in ignition area between clear and rainy conditions, the Hiroshima proxy still assumes $\tau = 1.0$ for all ignition scenarios. Atmospheric constituents all selectively absorb varying wavelengths of thermal radiation.[30] Water vapor, carbon dioxide, and other atmospheric aerosols create selective absorption bands, meaning atmospheric transmittance is not a single number, rather it is a spectrum-dependent function. The Hiroshima proxy's assumption that $\tau = 1.0$ brushes past this complexity almost entirely. Additionally, the nuclear fireball itself generates smoke, dust, and picks up debris from the detonation site that attenuates its own thermal pulse-a

[25] Liqun Lin et al., "Multi-Scale Influence Analysis of Urban Shadow and Spatial Form Features on Urban Thermal Environment," Remote Sensing 15, no. 20 (2023): 4902, https://doi.org/10.3390/rs15204902.
[26] Caroline Stillitano, "Understanding California's Climate Zones," University of San Diego, May 2025, https://digital.sandiego.edu/cgi/viewcontent.cgi?article=1043&context=npi-sdclimate.
[27] Gerald C. Holst, "Common Sense Approach to Thermal Imaging," Chapter 5: Atmospheric Transmittance, SPIE, 2000, https://doi.org/10.1117/3.2588945.ch5.
[28] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons (Washington, DC: U.S. Department of Defense, Energy Research and Development Administration, 1977).
[29] *Ibid*, FIGURE 7.42.
[30] "PACE: Overview," NASA, accessed March 2026, https://pace.gsfc.nasa.gov/.

phenomenon, described by Martin and Broido (1963) as self-obscuration.[31] For surface bursts (which penetrate deeper into the ground and thus loft more debris/material), this effect is more pronounced, and has the potential to reduce effective fluence by 20-40% compared to much cleaner airbursts.[32] The amount of combustible material present also depends on urban geometry.

As will be discussed in the following sections, there are a plethora of assumptions that barrage research on fuel density, urban geometry, and morphology. This illustrates that one assumption can greatly affect the outcomes of research on multiple aspects of the mechanism chain, and accurate information builds on the accuracy of the overall model itself. The 1977 model treats urban targets as if they were uniform surfaces, sometimes even flat surfaces, with a constant density of 4 g/cm².[33] Modern urban environments exhibit much higher levels of spatial heterogeneity, and are constructed with different materials (e.g., steel, concrete and glass, with lower combustibility, and plastic/other synthetics that produce 2-3x more soot than wood). GHSL-based urban fuel load modeling and ESA World Cover fuel regime classification (detailed in following sections) provide the spatially explicit fuel data needed to move beyond the uniform 4 g/cm² assumption. The work demonstrates that modern tools and datasets exist that can replace the Hiroshima proxy's geometric simplification with empirically grounded spatial fuel distributions.

Thermal radiation is the primary driver of firestorm formation, and it occurs in two distinct phases or pulses for air bursts at altitudes below 100,000 feet— the first pulse releases UV radiation lasting only milliseconds which is largely absorbed by the atmosphere (does not contribute to ignition); and the second pulse contains 99% of the total thermal energy, lasting several seconds (0.2-0.5 for a Hiroshima sized event).[34] As previously mentioned, the Glasstone and Dolan (1977) equation assumes a fixed ignition threshold or thermal fluence of 10 cal/cm²; the threshold is simplified and fixed largely for modeling purposes.[35] The actual ignition capability depends on the peak intensity and the rate at which the energy is deposited over time.[36]

Glasstone and Dolan also acknowledge that physics dictates that as the yield increases, the duration of the thermal pulse also increases.[37] If higher yield weapons are accompanied by significantly longer and slower pulse durations, this lowers the instantaneous power relative to the total energy.[38] While a 1-kiloton airburst has a pulse duration of about 0.4 seconds, a 10-megaton explosion has a pulse duration of more than 20 seconds.[39] Materials with high thermal inertia (thick wood, wet materials, or dense plastics) require higher instantaneous flux to overcome heat loss through conduction. Slower energy depositing allows more heat to dissipate before ignition temperature is reached. The fixed 10 cal/cm² threshold assumes instantaneous delivery. For materials with thermal inertia, perhaps a different visualization of the effective threshold could be:

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[31] S. Martin and A. Broido, Thermal Radiation and Fire Effects of Nuclear Detonations, USNRDL-TR-652; DASA 1376 (San Francisco, CA: Naval Radiological Defense Laboratory, May 10, 1963), 48, firedoc.nist.gov/article/eHcyXYQBWEcjUZEYbIXm.
[32] S. Martin and A. Broido, Thermal Radiation and Fire Effects of Nuclear Detonations, USNRDL-TR-652; DASA 1376 (San Francisco, CA: Naval Radiological Defense Laboratory, May 10, 1963).
[33] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons (Washington, DC: U.S. Department of Defense, Energy Research and Development Administration, 1977).
[34] *Ibid.*
[35] *Ibid.*
[36] *Ibid.*
[37] *Ibid.*
[38] Harold L. Brode, "Thermal Radiation from Nuclear Explosions," Report, RAND Corporation, August 1963, https://www.rand.org/content/dam/rand/pubs/papers/2008/P2745.pdf.
[39] Samuel Glasstone and Philip J. Dolan. The Effects of Nuclear Weapons.

$$Q\_\text{effective} = Q \text{ x } f\,(\text{thermal\_pulse, material\_properties})$$

Where a longer thermal pulse translates to a higher required effective ignition threshold.[40]

Increasing weapon yields trigger longer pulse durations, and these increased timeframes provide time for smoke and debris from initial ignitions to accumulate in the fireball's line-of-sight, attenuating thermal radiation reaching outer zones.[41] For a 20-second pulse, fires ignited in the first 5 seconds produce smoke that shields areas at the periphery for the remaining 15 seconds, thus effectively reducing the ignition radius below the geometric prediction from Glasstone and Dolan.[42] This inherently limiting mechanism is absent from the Hiroshima proxy, which treats thermal radiation as a static geometric pattern, rather than a time-evolving process. In moving beyond the Hiroshima proxy towards something more inclusive of modern conditions and atmospheric science, a realistic model must account for the spatial and temporal variability this research has identified. An updated ignition probability field would therefore include:

1. Spatially and temporally varying transmittance (τ)
2. Topographic factors, including terrain shadows
3. Spatially explicit fuel density from satellite data
4. Local wind speed affecting convective cooling during the pulse
5. Relative humidity affecting ignition threshold
6. Updated pulse duration (as it increases with yield) affecting thermal inertia

Rather than a single ignition radius defining a circular "tile," this framework would produce a probability field where ignition likelihood varies spatially based on specific local conditions. To conclude, in the literature, a static calculation is being used to predict an inherently complex and dynamic atmospheric event, which can produce inaccurate if not dangerous assumptions. Thermal ignition and being able to accurately estimate the fire zone boundary for a given target is essential to working through the rest of the nuclear winter mechanism chain. Assumptions in thermal ignition, like how anything and everything inside this fire zone boundary or line is assumed to burn in a post-detonation firestorm and be immediately lofted into the atmosphere. This is not always the case, and as usual, the reality is far more complex.

3.2 Firestorm Formation and Soot Injection

Firestorm formation and dynamics represent the weakest link in the nuclear winter mechanism chain, primarily due to there being only a few smaller scale historical examples (e.g., Hiroshima, Dresden, and Tokyo). A number of foundational papers including TTAPS (1983) and Robock (2007), as well as earlier work from Chandler (1963) and Brode (1981), treat firestorm formation as an almost automatic consequence of nuclear detonation over urban areas. The emerging assumption is that any weapon with sufficient yield detonated over a city with adequate fuel load will generate a firestorm that injects soot

[40] S. Martin and A. Broido, Thermal Radiation and Fire Effects of Nuclear Detonations, USNRDL-TR-652; DASA 1376 (San Francisco, CA: Naval Radiological Defense Laboratory, May 10, 1963).
[41] S. Martin, "Ignition of Organic Materials by Radiation," Fire Research Abstracts and Reviews 6 (1964): 85.
[42] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons (Washington, DC: U.S. Department of Defense, Energy Research and Development Administration, 1977).

into the upper atmosphere. In reality, a firestorm requires a number of specific conditions in order to form, as it sustains its own wind system in a vacuum chamber. The complex physics connecting thousands of individual ignitions to a single, self-sustaining, soot-lofting convective column is rarely interrogated.

The canonical Hiroshima model also assumes that a 15-kiloton atomic bomb creates a 13 km^2 firestorm, and that firestorm radius scales with the square root of weapon yield.[43] In other words, there is a linear relationship between the firestorm area, and weapon yield. The scaling relationship is based on the area exposed to critical thermal force, but it conflates correlation with causation. Just because Hiroshima's 15-kiloton airburst (580-600 m above) correlated with a 13 km^2 firestorm, does not mean the relationship is deterministic or generalizable to other events. Many nuclear winter models, including TTAPS' Climate and Smoke: An Appraisal of Nuclear Winter (1990), assume complete fuel consumption over approximately five hours: "These cloud condensation nuclei (CCN) fractions are not significantly larger after five hours of aging. The laboratory results for wood smoke are consistent with extensive data collected in a series of large-scale field burns."[44] This assumption ignores the dynamic nature of fire behavior, as fires can grow, peak, and decay in ways that depend on fuel continuity, atmospheric/ meteorological conditions, and the feedback between heat release and inflow winds.

In *The Effects of Nuclear Weapons* (1977), Glasstone and Dolan identified four necessary conditions for mass fire formation based on World War II firestorms: (1) burning area greater than or equal to 1.3 km^2; (2) simultaneous ignition of more than 50% of structures (on fire at once, time constant); (3) fuel loads are more than 4 g/cm^2; and (4) ambient near-surface winds of less than 3.6 m/s.[45] It is important to note that these conditions describe a "mass fire," which is not necessarily the same as a firestorm capable of deep atmospheric soot injection.

The critical distinction that leads to a possible climate effect is firepower and vertical transport: the heat release rate, or pyro-convective force must be strong enough to punch a deep plume into the atmosphere (upper troposphere or lower stratosphere) that self-organizes inflow.[46] More recent wildfire literature suggests there is a pyro-convective firepower threshold (PFT) below which fires remain trapped at lower altitudes; this threshold cites the minimum.[47] The relationship between instantaneous heat release rate, mass consumption rate, and lofting efficiency remains poorly characterized for urban area conflagrations.[48] By calculating the heat within each fire cluster, it is possible to compare to evaluate if it is larger than the PFT to be categorized as "firestorm capable." This is evaluated further in the following sections.

Moreover, the assumption of homogeneous fuel loads is particularly concerning for firestorm formation dynamics. Modern cities are not uniform blocks of combustible material that burn at a fixed rate, and they exhibit complex spatial heterogeneity that varies by city. Whether actively burning yet distinct zones can coalesce into a self-sustaining firestorm depends critically on fuel continuity, which can vary dramatically across urban environments. Strong winds can disrupt convective flow, low fuel

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[43] Craig C. Chandler et al., "Prediction of Fire Spread Following Nuclear Explosion," U.S. Forest Service, U.S. Department of Agriculture, 1963, https://www.fs.usda.gov/psw/publications/documents/psw_rp005/psw_rp005.pdf.

[44] R. P. Turco et al., "Climate and Smoke: An Appraisal of Nuclear Winter," Science 247, no. 4939 (January 12, 1990): 166–176, https://atmos.uw.edu/~ackerman/Articles/Turco_Nuclear_Winter_90.pdf.

[45] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons (Washington, DC: U.S. Department of Defense, Energy Research and Development Administration, 1977).

[46] Kevin Tory, "Pyrocumulonimbus Firepower Threshold: A Pyrocumulonimbus Prediction Tool," Weather and Forecasting 36, no. 2 (April 2021): 463–478, https://journals.ametsoc.org/downloadpdf/view/journals/wefo/36/2/WAF-D-20-0027.1.pdf.

[47] *Ibid.*

[48] *Ibid.*

density can limit heat release, and delayed ignitions can prevent the vital feedback loop for firestorm self-organization.

When taking into consideration the depth and complexity of the above assumptions about firestorm behavior, our approach involved establishing a foundational understanding of several key concepts before advancing to a more complex analysis. Firestorm formation is both the second stage of the mechanism chain, and one of the primary areas of inquiry for our research, as the field's understanding of firestorm behavior in relation to soot lofting and atmospheric injection is lacking. It is also the most consequential in being able to estimate shallow versus deep atmospheric injection. Even so, most literature treats the firestorm formation stage as a sort of mysterious linear process. All of the complexity is glossed over and hidden behind a number of key assumptions and estimations: a 15-kiloton weapon generated a km^2 firestorm; the fuel load is a uniform 4 g/cm^2; and the firestorm burns for about 5 hours and anything past this is insignificant. These estimations were largely consistent across relevant scholarship.

Firestorm formation dynamics are inherently complex; there are a plethora of calculations and physics that connect distinct individual ignitions to a massive, unified soot-lofting column. If assumptions about firestorms are oversimplified or outdated, then every following stage of the nuclear winter mechanism chain model, including soot mass, atmospheric injection, and global circulation, will also be affected. Compared to other steps in the mechanism chain, the field's understanding of firestorm formation and dynamics is the weakest link, thus in this phase of research we focused on understanding how and when a firestorm actually forms, rather than assuming that mass fires are equivalent to firestorms.

One critical differentiating factor in our analysis is distinguishing between correlation and causation regarding firestorm formation. While the 15-kiloton airburst over Hiroshima correlated with a 13 km^2 firestorm, this does not establish a direct causal scaling based on yield alone. Firestorm behavior is a complex function of an array of variables including fuel continuity, ignition simultaneity, atmospheric conditions, and feedback between heat release and inflow winds— none of which scale linearly with yield. As previously noted, the assumption of homogenous fuel is also problematic; modern urban environments consist of heterogeneous non-uniform zones of combustible material, ranging from dense downtown cores to sparse residential/suburban, highways, parks, and industrial areas. Each possesses drastically different fuel densities and combustion characteristics. Applying a single, antiquated average fuel load ignores this critical spatial variability, thus creating the risk of inflating soot production estimates. Each of these assumptions and insights reframed our research direction in working through firestorm formation, behavior, and dynamics. Rather than merely quantifying soot production, the critical inquiry became: what physical conditions dictate the transition of a burning area into a self-sustaining firestorm capable of lofting soot into the upper atmosphere?

A pivotal point in this research emerged from revisiting and re-examining Glasstone and Dolan's *The Effects of Nuclear Weapons* (1977). Moving beyond the singular case of Hiroshima, their analysis synthesized common conditions observed in World War II firestorms, including those in Hamburg, Dresden, and Tokyo. As previously mentioned, Glasstone and Dolan established four specific thresholds for such events: (1) A burning area that exceeds approximately 1.3 km^2; (2) Simultaneous ignition of more than 50% of structures; (3) Fuel loads exceeding ~4 g/cm^2; and (4) Low ambient surface winds (less than ~3.6 m/s).[49]

[49] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons (Washington, DC: U.S. Department of Defense, Energy Research and Development Administration, 1977).

These insights are essential, as they reframe firestorms as conditional phenomena rather than automatic or inevitable outcomes. A significant urban mass-fire could burn and occur without evolving into a self-sustaining firestorm if any one of these conditions were unmet: strong ambient winds can disrupt inflow patterns, low fuel density could limit total thermal release, and delayed ignitions can prevent the positive feedback loop necessary for self-organization. However, these factors alone primarily describe mass fires, and not necessarily a firestorm capable of generating nuclear winter effects. The critical distinction for nuclear winter modeling was vertical transport. The primary driver of global climatic impact is not surface-level combustion itself, but rather pyro-convection intense enough to inject soot into the upper troposphere or lower stratosphere.

This distinction demonstrated possible connections between firestorms and large wildfires; thus, we engaged with modern wildfire literature, in particular, studies regarding pyrocumulonimbus (pyroCb) events. These specific wildfires generate enough thermal energy to create their own storm systems, effectively "punching" smoke through the atmosphere. Central to this analysis is the Pyro-convective Firepower Threshold (PFT), which defines the minimum heat release rate required for a mass fire to transition into an actual firestorm.[50] In simplified terms, if the instantaneous firepower (Q) exceeds this threshold, the firestorm system can sustain deep convection; otherwise, the smoke remains trapped at lower altitudes of the atmosphere.

One of the central challenges in this analysis was synthesizing the wide breadth of firestorm behavior literature into something computational. While estimating total fuel mass is largely a straightforward calculation, calculating instantaneous firepower requires establishing the rate at which fuel is consumed over time. The traditional assumption of a flat five-hour burn is not sufficient for this purpose. Fire behavior is inherently dynamic— it grows, peaks, and decays. In order to address this, I developed a structured "decision tree" for firestorm formation, shown in appendix E. This diagram maps the mathematical progression from categorizing a burning cluster, to a firestorm.

The decision-making architecture starts with evaluating whether a cluster of actively burning tiles exists. If aggregate burn area does not exceed the pre-defined minimum threshold, the process terminates. If the threshold is exceeded, the next checks evaluate ignition simultaneity, fuel density, and wind conditions. Only when all mass-fire criteria are met does the model proceed to the final check: whether the cluster's firepower exceeds the Pyro-convective Firepower Threshold (PFT).

To provide a more robust foundation for this analysis, we evaluated three distinct methods for modeling the mass consumption rate: a constant burn rate (static); a time-variant profile (rise-peak-decay); and a radius dependent spread model in which firepower grows as the burning radius expands. While each approach involves inherent tradeoffs in computational complexity and empirical realism, they collectively represent an improvement over static assumption. This framework redefines firestorm formation from an opaque "black box," into an algorithmic decision process. This allows the model to produce more nuanced outcomes where large fires may occur without triggering nuclear winter effects, which has major implications for diving into scenarios.

Although this analysis is not comprehensive, it breaks down both the black-box treatment of the firestorm formation stage and unravels the assumption that all detonations with sufficient yield and fuel load would form a soot-injecting firestorm. Subsequent phases of this research will entail refining the consumption rate model in collaboration with the rest of the research team, leveraging modern wildfire research to better quantify the PFT and formalizing the link between firestorm formation and lofting efficiency. While these questions remain open, they are now clearly defined gaps

[50] Kevin Tory, "Pyrocumulonimbus Firepower Threshold: A Pyrocumulonimbus Prediction Tool," Weather and Forecasting 36, no. 2 (April 2021): 463–478.

rather than going unaddressed in the literature. Through deconstructing firestorms into physical criteria rather than relying on historical analogies, this work moves the project toward a more transparent and defensible understanding of nuclear winter climatic effects. Instead of assuming a catastrophic outcome, we can now determine precisely and quantitatively, the conditions under which it actually occurs.

3.3 Fuel Load Estimates

Current nuclear winter models do not adequately account for the heterogeneity of modern urban fuel loads, producing a significant uncertainty in the literature and in our overall understanding. Dense downtown city-centers melt gradually into suburbs, and are highly interwoven with industrial zones, highways, parks, and other areas all with drastically different fuel densities. Glasstone and Dolan estimated that firestorms could occur under a fuel load of (at least) 4 g/cm², relying on World War II-era observations from over 69 mass fires.[51] Applying this as a uniform fuel load across entire urban areas risks either overestimating or underestimating soot production depending on the specific target and its characteristics.[52] Additionally, modern urban areas are constructed with different materials, as they prioritize high-performance, prefabricated materials, and materials like reinforced concrete over traditional, local, or simple steel or wood-frame construction.[53] All of this contributes to the increased density of modern urban environments.

Furthermore, the role of interior building contents (e.g., furniture, appliances, electronics, consumer goods, etc.) compared to structural materials remains poorly quantified. All of these materials burn differently and less uniformly than untreated wood. More recent work like the COMBUST study from Uhl et al. (2025) on gridded combustible mass in the U.S. built environment represents a significant advance, although it is geographically limited to the United States which complicates model scalability.[54] On account of these uncertainties, this analysis focuses primarily on fuel loads in modern cities by utilizing modern datasets and computational tools to generate more accurate representations that propagate through each subsequent stage of nuclear winter modeling.

In the context of this research "fuel load," refers to the total mass of combustible material per unit area (kg/m² or g/cm²) that is available to be ignited and burned by nuclear detonations in specific target areas.[55] Higher fuel loads are necessary to generate firestorms, leading to soot lofting if the firestorm is capable of injection. Fuel load encompasses structural building materials and interior contents, and it acknowledges that modern cities are not uniform but consist of a mix of downtown, suburban, and industrial zones with varying densities, rather than relying on outdated, uniform Cold War-era assumptions. Fuel loads are a central component of nuclear winter modeling as the soot

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[51] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons (Washington, DC: U.S. Department of Defense, Energy Research and Development Administration, 1977).

[52] Owen B. Toon et al., "Rapidly Expanding Nuclear Arsenals in Pakistan and India Portend Regional and Global Catastrophe," Science Advances 5, no. 10 (October 2, 2019), https://people.envsci.rutgers.edu/lilixia/assets/pubs/20191002/rapidly_expanding_nuclear_arsenals_in_Pakistan_and_India_portend_regional_and_global_catastrophe.pdf.

[53] Chiemela Victor Amaechi, et al., "An overview of composites as construction material for the development of sustainable structures." Materials Today Sustainability, volume 33, March 2026.

[54] Johannes H. Uhl et al., "COMBUST: Gridded Combustible Mass Estimates of the Built Environment in the Conterminous United States (1975-2020)," Cornell University ArXiv, Physics and Society, November 12, 2025, https://arxiv.org/abs/2511.08893.

[55] National Academies of Sciences, Engineering, and Medicine, Potential Environmental Effects of Nuclear War, Chapter 3: Fire Dynamics and Emissions, (Washington, DC: The National Academies Press, June 2025).

produced during fuel mass combustion is the dominant driver of climate response, thus creating a nuclear winter effect. Older studies rely on outdated urban assumptions, both in material composition and city architecture, that are no longer representative of the current built environment. Our research on fuel loads centered on the following key question: given modern cities, how much combustible material (kg/m2) actually exists at plausible nuclear targets?

To address this question, we deconstructed the problem into three sequential steps: first, calculate the geometry and floor area for a given city; second, quantify the material intensities per square meter; and third, model the combustibility of those materials. For the initial step, we utilized Copernicus' Global Human Settlement Layer (GHSL) dataset as the authoritative, global, reproducible source for built-up surface area. The open-source GHSL data leverages Earth observation data and population censuses to enhance understanding of human presence on Earth.[56] Calculating the geometry and area for a given city also involves estimates for "built-up" areas within a given polygon. New Delhi, India was used as a case study for this methodology, and the code displayed in Appendix D.

For New Delhi, the total built up area in meters squared is equal to 548,027,287 m^2. After the total built-up area, we calculated the material intensity per meters squared. To accomplish this, we utilized the Deetman et al. *Global Construction Materials Database* (2020) as the core dataset. This dataset includes 26 global regions (IMAGE model), the material intensities (kg/m^2 floor area) for each region, and categorizes all buildings by dwelling type, which includes: detached; row/ semi-detached; apartment; and high-rise.[57] This dataset allowed us to utilize region-specific modern construction data and distinguish floor area from ground footprint, all from a global perspective. For each city, we extracted the region-specific material intensities for: concrete; steel; wood; glass; aluminum; and copper. To determine the average number of floors per building we utilized assumptions informed by Indian zoning regulations and typical building characteristics in comparable Asian urban areas.[58] We also assigned average floor numbers by dwelling type and computing a weighted average by using the quantity distribution of each building type within the study area. While this method did not yield the same level of precision achieved through direct measurement in other calculation steps, the estimations were both reasonable given available data constraints and defensible based on regional construction norms.

From utilizing the material intensities from Deetman et al. (2020) and weighting them by dwelling shares, we were able to model a defensible estimation of total material breakdown by city. We subsequently weighted each material in terms of combustibility, with materials like wood being weighted significantly heavier than concrete or steel. These weights were informed by National Institute of Standards and Technology (NIST) fire engineering ranges, although it is important to note that ranges are still assumptions.[59] In working through these steps, we were able to produce a reproducible model and develop a new methodology for the fuel load intensity (kg combustible / m^2 floor) and total combustible mass (in Tg per city). In subsequent research, this model could be expanded upon using newly published data from the Uhl et al. (2025) *COMBUST* study, particularly

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[56] "GHSL - Global Human Settlement Layer," Copernicus, 2026, https://human-settlement.emergency.copernicus.eu/.

[57] Sebastiaan Deetman et al., "Global Construction Materials Database and Stock Analysis of Residential Buildings between 1970-2050," Journal of Cleaner Production 247 (February 20, 2020), https://www.sciencedirect.com/science/article/pii/S0959652619340168.

[58] "Zoning and Land Use in India | Laws, Types, Colour Codes, and Rezoning Process," Lease Warehouse India, September 12, 2025, https://leasewarehouse.in/blog/post_details/235.

[59] Long T. Phan et al., "Best Practice Guidelines for Structural Fire Resistance Design of Concrete and Steel Buildings," NIST Technical Note 1681 (Gaithersburg, MD: National Institute of Standards and Technology, 2010), https://nvlpubs.nist.gov/nistpubs/technicalnotes/nist.tn.1681.pdf.

in relation to quantifying plastics in modern cities and how they contribute to fuel load.[60] The first iteration of calculating combustible material was meant to be a rough estimate, and the methodology will be improved upon with *COMBUST* data in upcoming research. Additionally, subsequent work will focus on quantifying the interior contents of buildings, as well as finding more precise data for the model that could be combined with models on fuel and land classification.

3.4 Nature of Combustible Material

While most nuclear winter and firestorm behavior literature models are based on urban targets, a significant percentage of sites likely to be targeted in a full-scale or limited nuclear exchange are in rural or semiurban locales. The density and composition of combustible materials/fuels in a metropolitan area like Manhattan differ greatly from the fuel loading of a region like eastern Montana, which houses a high concentration of Minuteman-III ICBM silos that would likely be targets in a theoretical nuclear exchange. Consequently, it is essential to categorize these distinct “fuel regimes” into different classifications and accurately quantify the combustible material in each specific regime/locale. Moreover, there is a strong degree of homogeneity within land type layers under the most common classification system; the Earth’s land types are described in ten layers, which is certainly reductive, but there are clearly fuel load distinctions between, for example, tree cover and grasslands, and built-up areas.[61] Intergovernmental Panel on Climate Change (IPCC) data is largely generalized— although necessary for creating global models, it can affect the reputability of estimates. In focusing on the nature of combustible material, we developed a fuel classification system, while also creating a model that can generate fuel load per m^2 at any location globally based upon the land schema classes.

To establish fuel regime categories, our research primarily utilized the ESA World cover 2021 dataset, a high-resolution global land cover product derived from European Space Agency (ESA) satellite platforms. This dataset provides 10-meter resolution globally, and uses preprocessed (e.g., cloud filtered, shadow masked, etc.) data for ingestion into a machine learning model that predicts land cover classification. The ESA World cover dataset documentation cites eleven generic land classes:

> The World Cover products are delivered in a regular latitude/ longitude grid (EPSG:4326) with the ellipsoid WGS 1984 (Terrestrial radius=6378 km). The legend includes 11 generic classes that appropriately describe the land surface at 10m: “Tree cover,” “Shrubland,” “Grassland,” “Cropland,” “Built-up,” “Bare/ sparse vegetation,” “Snow and Ice,” “Permanent water bodies,” “Herbaceous Wetland,” “Mangrove,” and “Moss and lichen.”[62]

The first step involved developing a practice script using the Google Earth Engine (GEE) to identify and extract land surface types, given the data and classifications listed above, as well as a selection of probable nuclear targets with their respective coordinates. The code used to initialize these target locations within the Google Earth Engine code editor, and the resulting imagery can be seen in Appendix A.

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[60] Johannes H. Uhl et al., “COMBUST: Gridded Combustible Mass Estimates of the Built Environment in the Conterminous United States (1975-2020),” Cornell University ArXiv, Physics and Society, November 12, 2025.

[61] “IPCC Good Practice Guidance for LULUCF,” Chapter 3: LUCF Sector Good Practice Guidance, IPCC, www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/Chp3/Anx_3A_1_Data_Tables.pdf.

[62] “ESA World Cover 2021 Global Land Cover Product at 10 m Resolution for 2021 Based on Sentinel-1 and 2 Data,” European Space Agency, 2021, worldcover2021.esa.int.

It is important to note that in the context of this analysis, however, the factor we need to classify is the actual area burnt, rather than just the particular coordinate set where the target or detonation is identified. Thus, it was necessary to integrate a "point and radius" system (radial search or buffer) upon which the total landmass of each land-surface is found. The radius is determined based upon the payload and coordinate points of the warhead detonation. This is variable, and because there is no uniform radius set for the code, a filler amount of five kilometers for visualization is used. One likely counterforce target in a large-scale nuclear exchange is the Air Force Academy in Colorado Springs, Colorado (38.998°, -104.858°), which is also a major command, control, and intelligence hub for the U.S. military. While the academy is a primarily educational institution, its proximity to NORAD's Cheyenne Mountain Complex, as well as Peterson Space Force Base and Schriever Space Force Base would make the area a likely target. The Air Force Academy coordinates were used as an example for the land classification methodology with the code seen in Appendix B along with the resulting imagery. For context on the map overlay, the color red indicates "built-up;" green indicates "tree cover;" and yellow indicates "grassland."

Closer analysis of the subject area pre and post land classification overlay indicates that the script accurately ascribes land cover classes to 10-meter pixels. While it is possible to classify different land categories, a model that can accurately estimate the amount of fuel in a particular radial area is necessary. Moreover, we need to attribute certain fuel loads to certain land classes to create fuel regimes. Based upon a wide array of studies, the measured fuel loads per kg per m^3 drastically vary for major land classes (tree cover, grassland, shrubland). For this reason, the code allows for variable inputs for fuel load per land class. The code script and resulting imagery in Appendix C includes example fuel load parameters (specifically for grassland, shrubland, and tree cover) for the Colorado Springs test target area.

Thus far we have developed a model for quantifying fuel load in target site areas based upon qualitative classification of land surface types derived from ESA data. This model will later be utilized to estimate the actual soot load that enters the atmosphere, and eventually, the stratosphere, in subsequent research. Before the model is fully deployed, it is necessary to more rigidly define singular fuel class load amounts (due to the drastic variation in extant fuel load kilograms per meters cubed estimates) so we can have a standard benchmark list for fuel reference, and furthermore rigidly define fuel burn percentages per land type, as there may be significant differences in amount of fuel load actually combusted (versus total before combustion) between fuel regimes. Once these uncertainties are fully defined and the model is paired to coordinates from a sample nuclear exchange target list, this script will serve as the foundation of our soot load quantity estimates for our lofting calculations, and later for modeling global circulation.

3.5 Targeting

Informing fuel load and combustion models with a comprehensive list of plausible targets is necessary in order to accurately estimate firestorm formation, soot injection, and later, global circulation. Counterforce targets, including military installations, hardened bunkers, and missile silo fields have variable fuel loads that are often much lower than dense urban areas. Many of these strategic targets are also more remote, located in closer proximity to rural agriculture and smaller downs rather than urban sprawl. Additionally, hardened targets likely require a ground burst to sufficiently penetrate and damage the target as opposed to an air burst which is typically used for urban locales. Air bursts are more efficient at initiating massive, widespread firestorms in cities due to unobstructed thermal radiation, while ground bursts channel concentrated energy into the ground, typically only generating localized fires, while resulting in a larger crater and more intense radiation.[63] Moreover, developing a comprehensive plausible target list is difficult as there are a number of uncertainties involved with approximating nuclear targets from open source and declassified information that can affect model accuracy, since current plans are highly classified.

Declassified intelligence reports from the Cold War, like the Red Integrated Strategic Offensive Plan (RISOP), identified and categorized many targets that strategists believed Russia would hit in the U.S., though this has likely changed. The Single Integrated Operational Plan, or SIOP was the U.S.' overall process and strategy for targeting and included a range of options for the president to choose from. It involved categorizing targets (counterforce or countervalue) and developing different attack strategies. In 2003, SIOP was replaced by OPLAN, or Operations Plan.[64] Strategic forces are assigned targets based on delivery system capabilities, target characteristics, priority, timing constraints, and damage requirements.[65] Declassified target lists from the Cold War show that the US prioritized air power targets in Russia due to the threats their bombers posed at the time.[66]

Calculations can certainly be accurate on a small scale (per target or target type), but ultimately these calculations would still technically be assumptions. Some of the uncertainties in estimating targets include warhead allocation per target; estimating exact coordinates of multiple detonations within one target; target phasing; how weapon types correspond to target classification; lack of comprehensive target list and lower accuracy of predictions; Russian versus Chinese Targets in the U.S.; and burst type. The number of detonations in each plausible baseline weapon employment scenario above could be considerably lower or higher in number depending on each adversary's choice.[67]

It is not possible to completely eliminate these uncertainties when drafting a targeting list— this is simply the nature of the information, and how targeting doctrines change often. It is also important to consider how much each uncertainty actually matters in producing research. Older nuclear winter models like TTAPS, Toon, and Robock also had to use a lot of estimation at the time when targeting doctrines were classified. Older models also focused on estimates from declassified intelligence which can provide accurate calculations but may not perfectly translate to actual modern targeting doctrine.

Open RISOP is one of the only publicly available databases, and although comprehensive, the methodology is not well documented.[68] David Teter, a civil engineer at Sandia National Lab for over 10 years, developed the database. At Sandia, Teter advised US STRATCOM, DIA, and DTRA on strategic plans, weapon effects, vulnerability analysis, and targeting of underground facilities, thus his expertise likely lent itself well to generating a dataset of this amount of detail. Some targets listed in Open RISOP would likely remain the same (e.g., Vandenberg AFB, RRMC, Ellsworth AFB, Colorado

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[63] Richard Wolfson and Ferenc Dalnoki-Veress, "The Devastating Effects of Nuclear Weapons," MIT Press, March 2022, thereader.mitpress.mit.edu/devastating-effects-of-nuclear-weapons-war/.

[64] "U.S. Changes Name of Nuclear War Plan," FOIA, Nuke Strat Archive, December 2004, nukestrat.com/us/stratcom/siopname.htm.

[65] U.S. Strategic Command, Annex C to USCINCSTRAT OPLAN 8044-98: Operations, January 25, 2001, declassified and released via FOIA on September 21, 2020, governmentattic.org/38docs/USSTRATCOMannexcOPLAN8044_2001.pdf.

[66] William Burr, ed., "U.S. Cold War Nuclear Target Lists Declassified for First Time," National Security Archive Electronic Briefing Book No. 538, December 22, 2015, nsarchive2.gwu.edu/nukevault/ebb538-Cold-War-Nuclear-Target-List-Declassified-First-Ever/.

[67] National Academies of Sciences, Engineering, and Medicine, Potential Environmental Effects of Nuclear War (Washington, DC: The National Academies Press, June 2025).

[68] David Teter, "Open RISOP (Red Integrated Strategic Operational Plan)," 2022, github.com/davidteter/OPEN-RISOP/tree/main.

Springs, Cheyenne Mountain, etc.) while others like missile silos in America's "heartland" would be different.

In order to estimate preliminary target lists that can be used in models, we developed a simple methodology that provides accurate information about targets and weapons used. The first step classified different kinds of targets and identified how much pressure (PSI) is required to inflict significant damage, as different targets require different kinds of warheads and delivery systems in order to ensure destruction. For example, hitting and destroying a small above-ground military base is much easier than destroying and disabling an entire silo field. The effects of the nuclear weapon come from yield, accuracy, burst height, and delivery method rather than the type of reaction itself— fission, fusion, or thermonuclear doesn't matter when looking at yield in kilotons. Open-source information from the Center for Strategic and International Studies (CSIS) Missile Threat database, as well as other public sources was utilized to draft lists of every nuclear-capable weapon from the United States, Russia, and China. These lists included the missile name, delivery system, arsenal context, stages, fuel type, as well as yield and payload.

Creating a fully comprehensive target list would look much like David Teter's Open RISOP, which has over 9100 detonations listed just for the United States. This is not feasible for a project like this, and we would rather focus on a smaller list of targets that are well-estimated and then proceed to determine whether the effects may be scaled linearly. Much of what determines combustible material depends on the environment or land type. Thus, in order to develop a target list, the United States was divided into ten geographical regions. Each region contains a set of targets of similar kinds (e.g., each region has a large military base, underground facility, command center, urban area, etc.). We also intend to utilize Teter's Open RISOP for randomized selections of targets, as his dataset has over nine thousand entries. As long as new models encompass a variety of different target types, as well as demonstrate the differences between urban sprawl, and smaller rural cities and towns, this will be a significant evolution in the literature. More detailed work on the project's targeting methodology and preliminary target lists can be seen in Appendix F.

4. Conclusion

When examined through a closer lens, the field's overreliance on assumptions and neglect of core uncertainties illuminates an interesting paradox: many of the assumptions this research explored are explicitly recognized in the foundational nuclear winter literature, yet the field has often systematically chosen to dilute them into static estimations, thus neglecting their inherent complexity. This reflects a methodological approach shaped by practical necessity, and one that prioritizes computational tractability and scenario comparability in an era of limited resources and urgent political timelines, rather than scientific negligence.

For example, values for atmospheric transmittance (τ) can significantly fluctuate based on visibility and meteorological conditions, which directly affects calculations for the ignition radius. Glasstone and Dolan (1977) explicitly acknowledge that atmospheric transmittance can range from 0.2 to 1.0, depending on conditions, yet default to $\tau = 1.0$ in all canonical calculations, despite the fact that different transmittance values produce radically different ignition areas (as shown in previous analysis on thermal ignition).[69] This pattern repeats throughout the entire nuclear winter mechanism

[69] Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons (Washington, DC: U.S. Department of Defense, Energy Research and Development Administration, 1977).

chain: firestorm formation treated as deterministic despite conditional physics; fuel loads assumed to be uniform despite the lack of spatial homogeneity in modern urban environments; soot injection heights assumed rather than derived from first principles.

Perhaps this is best understood through the historical foundations of the field itself. The nuclear winter sub-field emerged during the Cold War under intense political pressure to provide policy-relevant answers about extinction risk scenarios. Simplistic assumptions— like the Hiroshima proxy, and uniform 4 g/cm^2 fuel load— allowed researchers to produce quantitative estimates of global cooling and mortality that could inform policy, international nonproliferation architectures, as well as arms control negotiations. In a way, these assumptions became canonical over time not because they were empirically validated but because they provided more tractable answers to some of the world's biggest questions at the time. In order to effectively communicate the risk of nuclear weapons, quantitative answers to prove urgency that matched political were required.

As the broader field evolved amidst an era of waning political urgency on nuclear risk immediately post-Cold War, these simplifications calcified into doctrine. The 2025 National Academies study acknowledges many of the same assumptions we identified yet stops short of offering a concrete path forward. The report ends with recommending more research without charting how modern tools (e.g., satellite remote sensing, open-source datasets, global fuel databases, and high-resolution climate models) already exist to address them— perhaps reflecting the difficulty of doing so without dedicated funding and a broader research community invested in studying nuclear winter. This manifests through a perpetual cycle of reluctance to revisit foundational choices of the field orthodoxy, because doing so would likely require completely rebuilding models as we know them today with little resources and institutional interest. Our work demonstrates that returning to the foundations is both possible, and necessary.

Undeniably, this research requires extensive conversations across disciplines, rather than simply a pre-selected committee of senior experts producing broad statements that lack actionable solutions. When the same small group of experts— working under significant resource constraints— is asked to advance the field, it is natural that foundational assumptions remain stable across iterations. What the field needs is new voices and disciplines, not a repudiation of those who have kept this vital sub-field alive. We are entering an era of increasing nuclear risk with a tripolar geopolitical environment, emerging technology, and crumbling international norms. When nuclear winter models systematically overestimate climate effects, they risk losing credibility when scrutinized, which could potentially undermine arms control efforts. Conversely, if they systematically underestimate the effects (in particular for regional exchanges and higher modern weapon yields), the barrier to nuclear use may decrease if consequences are perceived to be less severe— which would produce far reaching and dangerous ramifications.

5. Research Agenda

By systematically addressing these uncertainties and assumptions, the field can move towards a more defensible and transparent assessment of the risk of nuclear winter. This research agenda broadly seeks to contribute to updating the nuclear field's foundational assumptions about the risk of nuclear war, reinterrogate assumptions and biases, and determine where more research and funding is required to fill the knowledge gap. The research agenda below is divided by focus areas that correspond to different stages of the nuclear winter mechanism chain:

5.1 Thermal Ignition

The Hiroshima proxy, a single datapoint on the ignition radius from the bomb dropped on Hiroshima in 1945, has essentially become doctrine, and is assumed to scale linearly to today's more modern, destructive, precise, and compact nuclear weapons in different delivery systems. The field uses the scaled Hiroshima proxy to predict nuclear winter, but we don't actually know what Hiroshima's atmospheric effects looked like, as it occurred before modern atmospheric monitoring existed.

1. How does the specific delivery system (e.g., gravity bomb, missile, etc.) and miniaturization of nuclear weapons affect the ignition radius?
2. What fraction of the 13 km^2 area actually burned in Hiroshima? And how much soot was produced per unit of fuel?
3. How does the relationship between firestorm size and weapon yield change as yields increase drastically from 15 kt to 800 kt?

5.2 Modern Firestorms

Current models are anchored in historical firestorm occurrences, of which there are only four: Hiroshima, Dresden, Tokyo, and Hamburg. All of these instances occurred during World War II, over 80 years ago. Although these firestorms can inform our basic understanding of firestorm behavior, they lacked the ability to gather scientific data from firestorms at the time. Additionally, the field's understanding of firestorms at the time was in its very early stages.

1. Can firestorms extend beyond the arbitrary radius established in thermal ignition literature?
2. What is the relationship between firestorm formation and size and exact air-burst height?
3. Can heuristic-based "spread-adjustment factors" for different land types approximate non-uniform fire growth without the computational overhead of full fluid-dynamic fire modeling?
4. In modeling causality and climate data, to what extent can a firestorm spread beyond its initial predetermined ignition radius?

5.3 Soot Injection Dynamics

Current models assume that all firestorms automatically inject soot, but this is not generalizable, and soot injection can be either weak or deep. Weak injection often penetrates the troposphere, while deep injection often penetrates the lower stratosphere where it sits and ages instead of being rained out. To cause a nuclear winter cooling effect and circulate, soot must be able to make it into the lower stratosphere.

1. How long can soot injection persist? Can soot injection be modeled temporally?
2. Does soot injection linearly decrease after 5 hours? Or can the strength of injection increase?
3. How do regional variations in fire intensity—driven by land-specific fuel loads—influence the initial injection height of soot into the stratosphere?

5.4 Secondary Organic Aerosols

A number of modern studies on soot injection and wildfires that our research evaluated discuss the presence of secondary organic aerosols (SOAs), which are fine atmospheric particles that can coat the surface of black carbon. By coating black carbon, SOAs alter the black carbon's chemical properties and change the optical depth, thus allowing the black carbon to absorb more light. The presence of SOAs could drastically change estimates on not only soot injection, but how the particles behave in the lower stratosphere.

1. Why have past nuclear winter models failed to consider the role of secondary organic aerosols?
2. What role do secondary organic aerosols play in altering the nuclear winter climate effect?
3. What are the differences between secondary organic aerosols and volatile organic aerosols (VOAs)?
4. What are the exact kinds of SOAs present in soot injection from a nuclear detonation? Does this change when evaluating the effect on a countervalue versus a counterforce target?

5.5 Combustion and Fuel Loads

As mentioned throughout this report, modern urban environments have different material compositions than in the past, including the widespread use of plastic, which releases different chemicals/aerosols when burnt. Fuel load and combustion estimates also need to account for the material composition inside the buildings, in addition to the built-up structures.

1. Without accurate data outside the United States, can our results be scalable?
2. To what degree are IPCC burn fractions globally representative?
3. Although it is a single datapoint from one region, and was not a firestorm from a nuclear detonation, can the Australian wildfire soot injection ratio (~ .02) be extrapolated to other urban and counterforce target areas?
4. To what degree can updated satellite-derived land-fuel classifications reduce the uncertainty intervals in regional burn-zone soot production?

5.6 Targeting

Estimating targets accurately is inherently complex, and by nature requires a degree of estimation. Although we can understand how targeting doctrine was operationalized during the Cold War through declassified intelligence from the U.S.' RISOP, the U.S.' current targeting doctrine, is obviously classified. Target composition, land type, detonation position, burst height, and warhead allocation per target are all important factors in how the rest of the mechanism chain evolves post-detonation, although there is little documentation on how to estimate this accurately.

1. What is the standard for warhead allocation per target, and how does this change across target types?
2. How is it possible to assume where on a target area the weapon will be detonated?
3. Are there standard field "norms" for which kinds of weapons would ideally hit specific types of targets?

4. What defines the difference between Russian and Chinese targets in the United States?
5. Which targets will be a priority over others if assuming strikes come in phases?
6. Does a target list need to be comprehensive (i.e., OPEN RISOP) to be considered accurate?

5.7 Global Circulation and Climate

Climate models are primarily designed to simulate long-term boundary and condition driven changes (e.g., global warming from 1980-2026) as opposed to climate events with a more sudden or chaotic onset like nuclear winter. Additionally, global circulation and climate predictions are highly dependent on accurate soot injection estimates that include the role of SOAs, and how this changes residence time in the stratosphere. Conventional narratives about nuclear winter generalize that the climate effect will be bad for x number of years (often hear 10), but they lack the ability to predict how stratospheric soot will deplete over time.

1. Can today's more advanced climate models (e.g., WACCM) help predict residence time better and show how it depletes linearly or non-linearly?
2. Can WACCM accurately represent injection if the forcing variable is only accounted for at its final destination (the lower stratosphere)?
3. Can Australian firestorm residence and dispersion patterns be extrapolated to nuclear war related global circulation patterns of soot?
4. How does the integration of variable, land-type-specific fire spread rates alter the projected total soot loading in Global Circulation Models (GCMs) compared to current circular burn radii assumptions?

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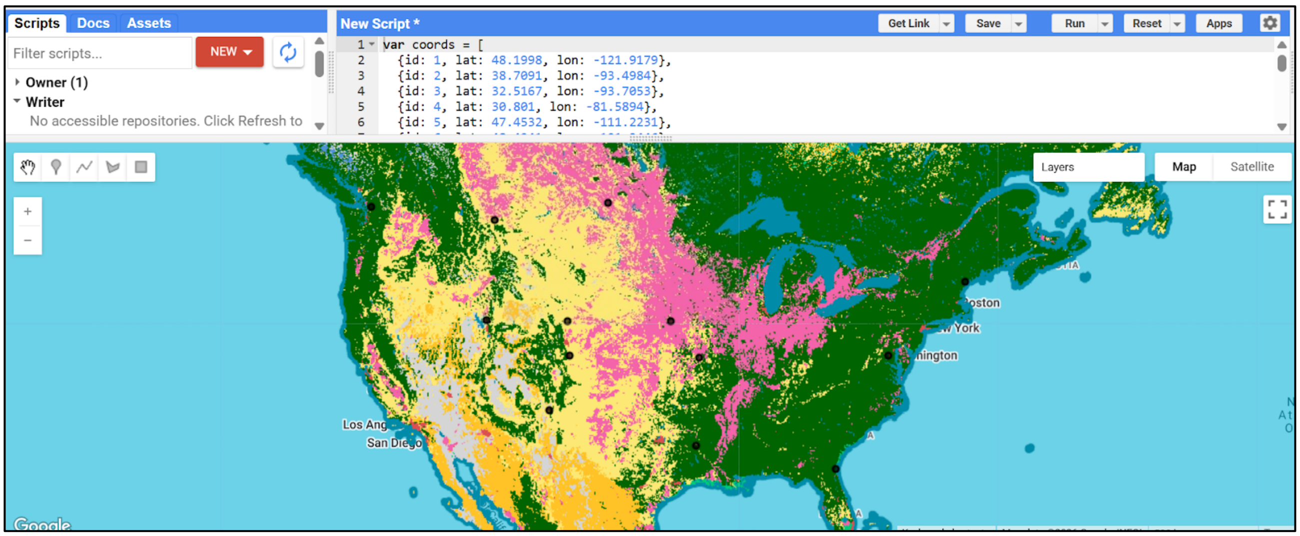
Appendix A

Initialization of locations within Google Earth Engine.

```
var coords = [
 {id: 1, lat: 48.1998, lon: -121.9179},
{id: 2, lat: 38.7091, lon: -93.4984},
{id: 3, lat: 32.5167, lon: -93.7053},
{id: 4, lat: 30.801, lon: -81.5894},
{id: 5, lat: 47.4532, lon: -111.2231},
{id: 6, lat: 48.4241, lon: -101.3446},
{id: 7, lat: 41.1603, lon: -104.8543},
{id: 8, lat: 35.0451, lon: -106.4625},
{id: 9, lat: 41.1804, lon: -111.9496},
{id: 10, lat: 43.6709, lon: -70.3135},
{id: 11, lat: 21.3483, lon: -157.9239},
{id: 12, lat: 38.8462, lon: -104.6971},
{id: 13, lat: 41.115, lon: -95.9727},
{id: 14, lat: 38.8641, lon: -77.052}
];
var fc = ee.FeatureCollection(coords.map(function(c) {return
ee.Feature(ee.Geometry.Point([c.lon, c.lat]), {id: c.id}); }));
var esa = ee.ImageCollection("ESA/WorldCover/v200") .first()
 .select('Map');
var esaLegend = ee.Dictionary({
10: ‘Tree cover’,
20: ‘Shrubland’,
30: ‘Grassland’,
40: 'Cropland',
50: 'Built-up',
60: 'Bare / sparse vegetation', 70: 'Snow and ice',
80: 'Permanent water bodies', 90: 'Herbaceous wetland',
95: 'Mangroves',
100: 'Moss and lichen'
});
var classified = esa.sampleRegions({
collection: fc,
scale: 10,
geometries: true
});
var withNames = classified.map(function(f) {
var code = ee.Number(f.get('Map'));
var name = esaLegend.get(code.format(), 'Unknown');
return f.set('land_class', name);
});
print('Classified coordinates:', withNames);
Export.table.toDrive({
collection: withNames,
 description: 'Landcover_Classification_ESA2021',
fileFormat: 'CSV'
});
 var vis = {
min: 10, max: 100,
palette: [
'#006400', '#ffbb22', '#ffff4c', '#f096ff', '#fa0000',
 '#b4b4b4', '#f0f0f0', '#0064c8', '#0096a0', '#00cf75', '#fae6a0'
```

```
]
};
Map.centerObject(fc, 5);
Map.addLayer(esa, vis, 'ESA WorldCover 2021');
```

Resulting imagery after initializing locations:

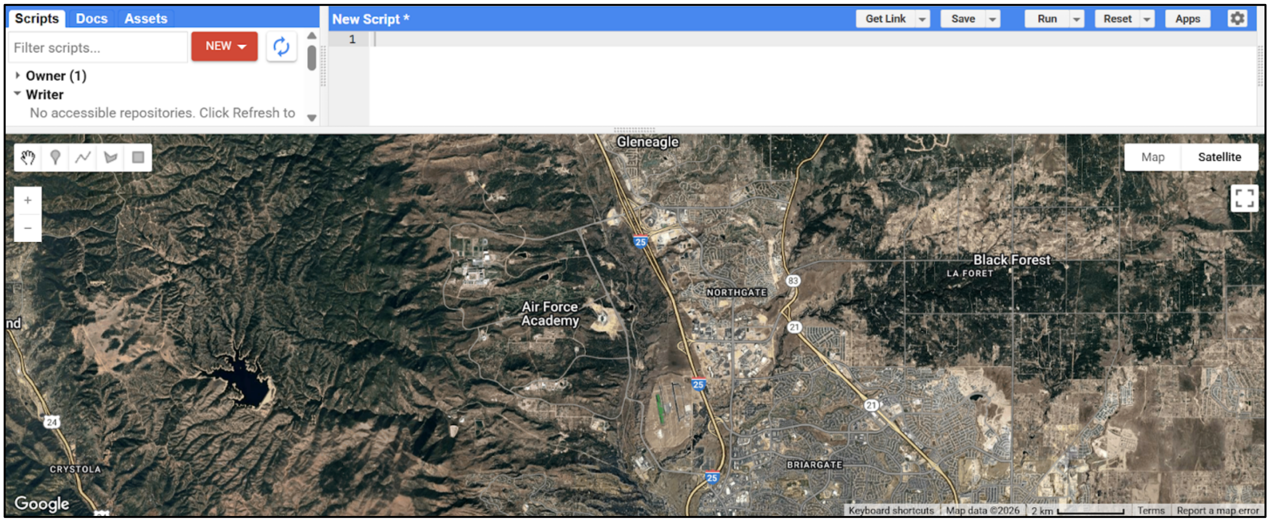


Appendix B

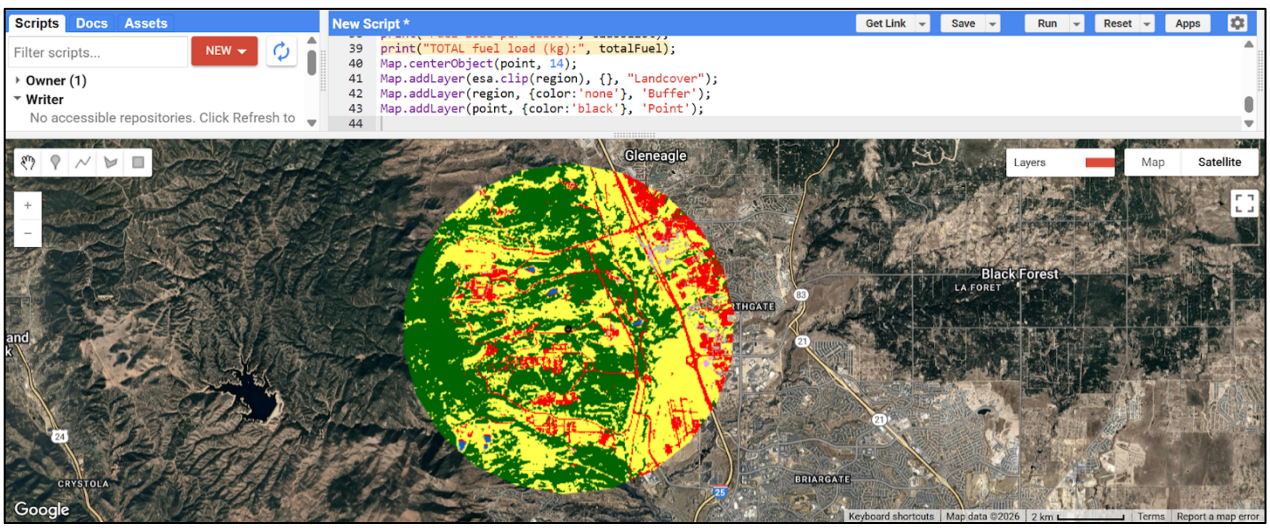
Land classification using the Air Force Academy in Colorado Springs, CO.

```
var lat = 38.998;
var lon = -104.858;
var radius_m = 5000;
var fuelLoads = ee.Dictionary({
      10: 0.0,
      20: 0.0,
      30: 0.0,
      40: 0.0,
      50: 0.0,
      60: 0.0,
      70: 0.0,
      80: 0.0
});
var esa = ee.Image("ESA/WorldCover/v200/2021").select("Map");
var point = ee.Geometry.Point([lon, lat]); var region =
point.buffer(radius_m);
var img = ee.Image.pixelArea()
      .addBands(esa)
      .rename(['area','class']);
var classStats = img.reduceRegion({
  reducer: ee.Reducer.sum().group({
      groupField: 1,
      groupName: 'class'
}),
      geometry: region,
      scale: 10,
      maxPixels: 1e12
});
var classList = ee.List(classStats.get('groups'));
var totalFuel = ee.Number(classList.iterate(function(entry, acc) {
      entry = ee.Dictionary(entry);
      var code = ee.Number(entry.get('class'));
      var area_m2 = ee.Number(entry.get('sum'));
      var load = ee.Number(fuelLoads.get(code, 0));
      var subtotal = area_m2.multiply(load);
      return ee.Number(acc).add(subtotal);
}, ee.Number(0)));
print("Fuel load per class:", classList);
print("TOTAL fuel load (kg):", totalFuel);
Map.centerObject(point, 14);
Map.addLayer(esa.clip(region), {}, "Landcover");
Map.addLayer(region, {color:'none'}, 'Buffer');
```

Area of interest pre-overlay.



Area of interest post-overlay.

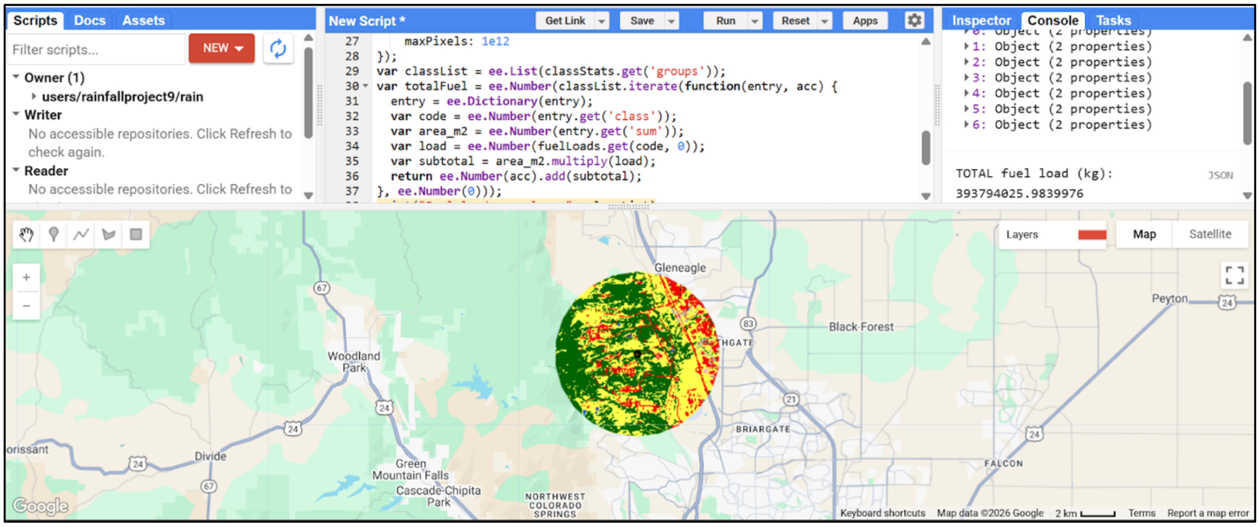


Appendix C

Example fuel load parameters for test area.

```
var lat = 38.998;
var lon = -104.858;
var radius_m = 5000;
var fuelLoads = ee.Dictionary({
      10: 11.0,
      20: 1.5,
      30: 0.5,
      40: 0.0,
      50: 0.0,
      60: 0.0,
      70: 0.0,
      80: 0.0
});
var esa = ee.Image("ESA/WorldCover/v200/2021").select("Map");
var point = ee.Geometry.Point([lon, lat]);
var region = point.buffer(radius_m);
var img = ee.Image.pixelArea()
      .addBands(esa)
      .rename(['area','class']);
var classStats = img.reduceRegion({
  reducer: ee.Reducer.sum().group({
      groupField: 1,
      groupName: 'class'
  }),
  geometry: region,
  scale: 10,
  maxPixels: 1e12
});
var classList = ee.List(classStats.get('groups'));
var totalFuel = ee.Number(classList.iterate(function(entry, acc) {
      entry = ee.Dictionary(entry);
      var code = ee.Number(entry.get('class'));
      var area_m2 = ee.Number(entry.get('sum'));
      var load = ee.Number(fuelLoads.get(code, 0));
      var subtotal = area_m2.multiply(load);
      return ee.Number(acc).add(subtotal);
}, ee.Number(0)));
print("Fuel load per class:", classList);
print("TOTAL fuel load (kg):", totalFuel);
Map.centerObject(point, 14);
Map.addLayer(esa.clip(region), {}, "Landcover");
Map.addLayer(region, {color:'none'}, 'Buffer');
```

Generated imagery, with total fuel load in the target area estimated at ~ 393 million kilograms.

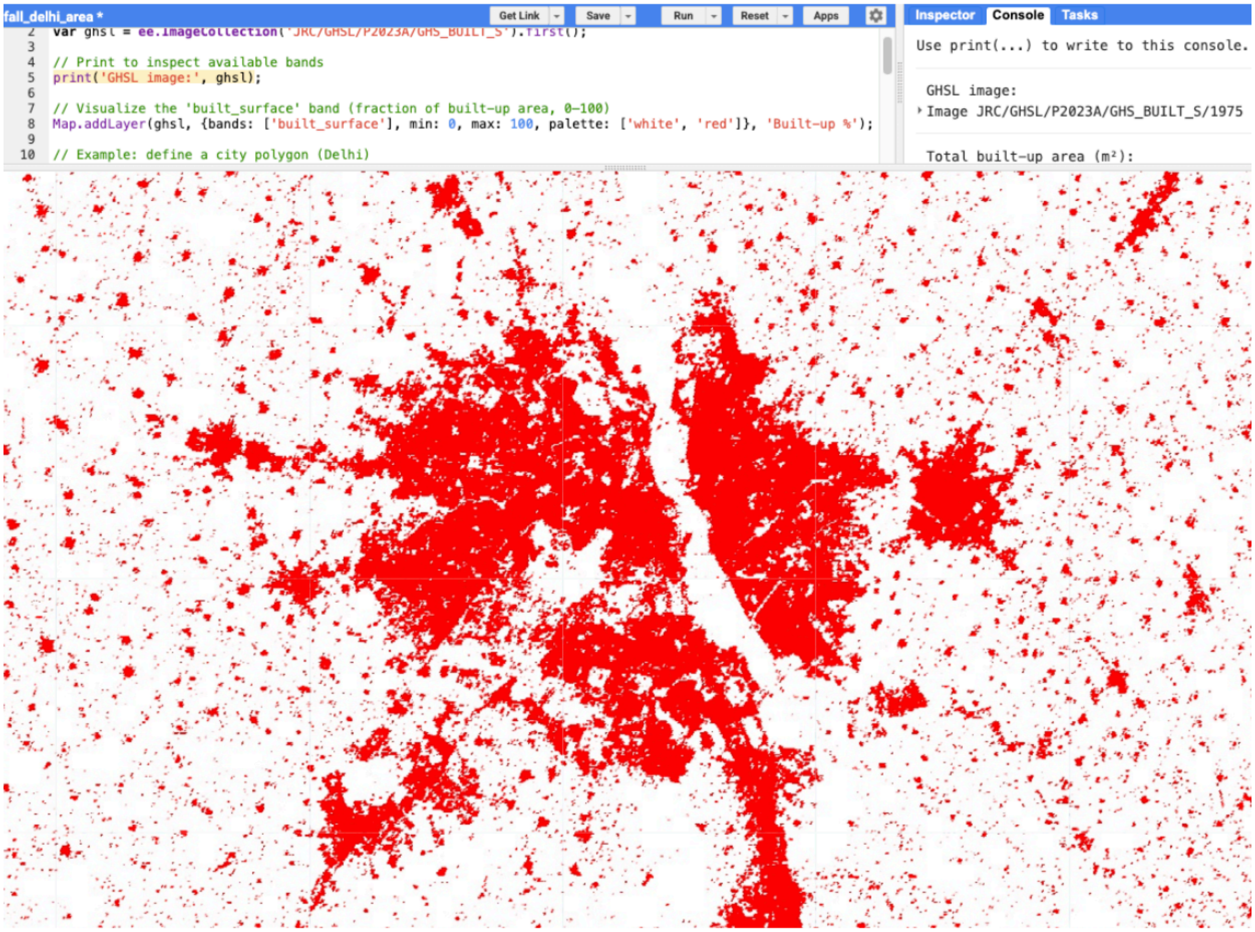


Appendix D

GHSL and built-up area calculations for New Delhi, India.

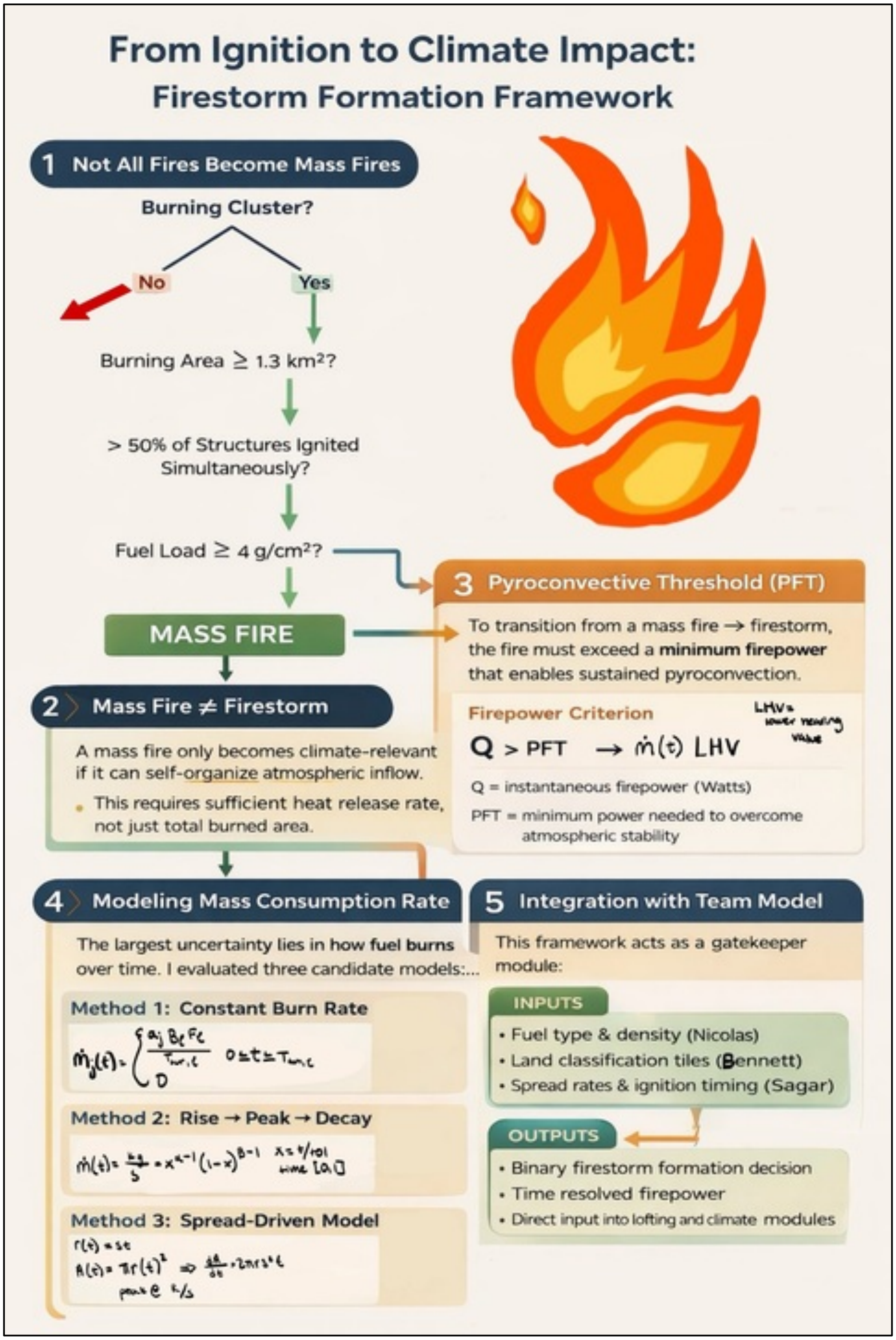
```
// Load the GHSL built-up surface dataset (P2023A)
var ghsl = ee.ImageCollection('JRC/GHSL/P2023A/GHS_BUILT_S').first();

// Print to inspect available bands
print('GHSL image:', ghsl);

// Visualize the 'built_surface' band (fraction of built-up area, 0-100)
Map.addLayer(ghsl, {bands: ['built_surface'], min: 0, max: 100, palette:
['white', 'red']}, 'Built-up %');

// Example: define a city polygon (Delhi)
var delhi = ee.FeatureCollection('FAO/GAUL_SIMPLIFIED_500m/2015/level2')
              .filter(ee.Filter.eq('ADM2_NAME', 'Delhi'));
Map.centerObject(delhi, 8);

// Mask to built-up areas above 50% (you can adjust threshold)
var builtMask = ghsl.select('built_surface').gt(50);

// Calculate total built-up area in m²
var builtArea = builtMask.multiply(ee.Image.pixelArea())
  .reduceRegion({
    reducer: ee.Reducer.sum(),
    geometry: delhi.geometry(),
    scale: 30,
    maxPixels: 1e12
});

print('Total built-up area (m²):', builtArea);
```

Resulting imagery for built-up area in New Delhi, India (red signifies "built-up")



Appendix E

Decision making framework for firestorm formation.



Appendix F

Targeting dataset sample— Russia targets in U.S.

Region	State	Target	Class	Lat/Long	Weapon	Yield	Allocation	Burst
Far West	CA	Los Angeles	Urban	34.0549°, 118.2426°	TU-160	200 kt	Single	Air
Rockies	CO	US NORTHCOM	Silo field	38.836166°, -104.694360°	SS-19	600 kt	Single	Ground
Rockies	CO	FE Warren AFB Missile Site N.05	Silo field	40.612222°, -103.763055°	SS-19	500 kt	MIRV	Ground
Rockies	CO	FE Warren AFB Missile Site N.06	Silo field	40.590000°, -103.897222°	SS-19	500 kt	MIRV	Ground
Rockies	CO	FE Warren AFB Missile Site N.08	Silo field	40.623889°, -103.993888°	SS-19	500 kt	MIRV	Ground
Rockies	CO	FE Warren AFB Missile Site 09	Silo field	40.945555°, -104.216666°	SS-19	500 kt	MIRV	Ground
Midwest	IL	Chicago	Urban	41.894786°, -87.629805°	TU-160	200 kt	Single	Air
Midwest	KS	McConnell AFB	Military	37.634532°, -97.253845°	TU-160	350 kt	Single	Ground
Plains	NE	US STRATCOM	C3/ Hardened	41.108569°, -95.934855°	RS-24 YARS	200 kt	Single	Ground
Mideast	DC	Pentagon/ White House	Strategic/ Military	38.893997°, -77.036623°	RT-2PM Topol ICBM	800 kt	Single	Air