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War Thermal Footprint: A Conceptual Framework for Quantifying the Thermal Effects of Warfare

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Introduction

Throughout the history of environmental science, important indicators have emerged from the observation and quantification of specific processes, like carbon footprint index, soil salinity index, vegetation stress index and various other environmental indices. This progression raises a new question: Can the environmental effects of warfare be detected, quantified, and mapped as a War Thermal Footprint using thermal remote sensing?

Warfare is a severe disturbance affecting natural and human systems. Explosions, fires, massive energy consumption, vegetation destruction, infrastructure damage, soil disturbance, and land-use change can alter surface properties and the energy balance of the land. Evidence from recent studies shows that warfare can produce substantial and persistent impacts on soils, vegetation, ecosystems, and landscapes. These effects may be more destructive in arid and semi-arid environments, where limited water availability and fragile ecosystems can slow recovery. Recent advances in thermal remote sensing, Earth observation, energy-balance modeling, and artificial intelligence provide new opportunities to detect and quantify such changes. Satellite-derived land surface temperature (LST) is an established measure of the thermal state of the land surface and can be retrieved over large areas using thermal infrared observations. Remote sensing and GIS have also increasingly been used to monitor environmental impacts associated with military activities.

Based on this potential, this editorial proposes the War Thermal Footprint (WTF) as a conceptual framework for assessing the measurable thermal disturbance of the Earth's land surface associated with warfare. The WTF is not intended to replace the carbon footprint. Rather, it provides a complementary perspective focused on the thermal response and disturbance of the land surface.

Definition and Proposed Framework

The War Thermal Footprint is proposed as an integrated spatio-temporal measure of thermal disturbance attributable to war-related activities. It may be characterized through changes in land surface temperature, thermal anomalies, surface radiation, energy-balance components, and associated ecosystem responses detected by thermal remote sensing, field observations, and physical models.

Satellite platforms such as MODIS, Landsat, ECOSTRESS, ASTER, and VIIRS can provide information on land surface temperature, thermal anomalies, hotspots, vegetation degradation, and changes in landscape thermal properties. Energy-balance models can further characterize changes in net radiation, sensible and latent heat fluxes, and soil heat flux. However, satellite-derived LST itself is subject to retrieval uncertainties and scale-related limitations that must be

considered when developing a quantitative indicator.

Artificial intelligence can support the framework by integrating multi-temporal satellite observations with environmental and contextual data, helping identify subtle patterns and distinguish war-related signals from background variability. However, AI should remain an analytical tool and cannot replace physical understanding, field observations, or independent scientific validation. A central challenge is attribution. Thermal anomalies may also result from drought, heatwaves, climate variability, urbanization, land-use change, or natural disturbances. Reliable WTF assessment therefore requires pre-conflict thermal baselines, suitable control areas, long-term time series, field observations, and physical models to separate war-related effects from other drivers. Ideally, WTF should be estimated against a counterfactual thermal trajectory representing the expected thermal state of the landscape in the absence of warfare.

Expected Results and Research Directions

The framework considers three temporal scales. Short-term effects may include explosions, fires, and intense thermal hotspots. Medium-term effects may include vegetation loss, changes in soil moisture and albedo, erosion, and altered surface energy balance. Long-term effects may include land-use change, reduced ecological capacity, and persistent changes in the thermal regime of the landscape.

The WTF could therefore be characterized through several complementary dimensions, including thermal anomaly intensity, affected area, persistence, associated vegetation response, and thermal recovery rate. Together, these dimensions could support spatial assessment of environmental disturbance and comparisons among conflict-affected regions.

A preliminary conceptual representation is:

WTF ∝ Thermal Anomaly × Affected Area × Persistence

This relationship is conceptual rather than a validated quantitative equation. It represents three fundamental dimensions of a thermal footprint: magnitude, spatial extent, and duration. Future research must establish appropriate units, coefficients, weighting schemes, uncertainty estimates, and validation procedures. Importantly, warfare does not necessarily produce only warming. It may increase or decrease surface temperature and alter the thermal regime through changes in vegetation, soil moisture, albedo, surface roughness, and energy exchange. Therefore, WTF should be understood as a measure of war-related thermal disturbance, rather than simply warming.

Future studies should combine pre- and post-conflict observations, control areas, satellite time series, field measurements, and energy-balance models to determine whether thermal changes can be reliably attributed to warfare and how long they persist. Existing research demonstrates that remote sensing can already reveal important spatial and temporal environmental changes associated with armed conflicts; the proposed WTF seeks to extend this capability specifically into the thermal domain.

Conclusion

The War Thermal Footprint is currently a conceptual proposal, not an established environmental indicator. Its potential value lies in complementing the carbon footprint by quantifying the thermal response of the Earth's land surface to warfare. The idea is deliberately presented as an open scientific question rather than a definitive metric. If future research demonstrates that conflict-related thermal disturbances can be systematically measured, reliably attributed, reproduced across different environments, and distinguished from natural

and climatic variability, the WTF could become a useful tool for environmental assessment, thermal remote sensing, ecological recovery monitoring, and post-conflict land management.

The purpose of this proposal is therefore not to provide a final index, but to initiate a new research direction. Its scientific value will ultimately depend on empirical testing, independent validation, open data, and international collaboration. War leaves many footprints. Some are visible in ruins and smoke; others may remain hidden in the thermal memory of the land.

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I would like to emphasize that this editorial is entirely scientific and conceptual in nature and is not intended to promote, support, or oppose any political position or agenda. At the same time, I must acknowledge that the wars and armed conflicts of recent years provided the immediate motivation for reflecting on the environmental and thermal dimensions of warfare and for developing the concept presented here. I therefore dedicate this editorial to all those who work for peace, dialogue, and the protection of our shared Earth. I am sincerely grateful to Dr. Ali Darvishi Boloorani, Professor of Remote Sensing at the University of Tehran, for his valuable guidance, constructive discussions, and thoughtful comments during the development of this idea. I also deeply appreciate the assistance and contributions of my students, Mr. Erfan Motaghiyan, Mr. Ali Sadeghi, Ms. Avin Meysami, Ms. Mina Azmi Panah, Ms. Lida Sadeghi and Mr. Ehsan Motaghiyan whose discussions and support were helpful in shaping this work. I am grateful to all colleagues and students whose scientific curiosity and commitment to understanding the Earth continue to inspire new questions and perspectives. Above all, I hope that science can contribute not only to understanding the consequences of conflict, but also to strengthening our shared commitment to peace and the preservation of the Earth for future generations.

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