Reply to Sullivan and Cruz: Defense of a simplified physical model

We thank Sullivan and Cruz for their thoughtful letter (1). They raise a very important point: an ignited strip of nitrocellulose is not a wildfire. The two systems differ in fuel, topography, and flame dynamics—to say nothing of scaling; direct links between them are difficult to draw. With this point, we agree completely.

Our intention, however, was not to create an experimental system that captures, in precise physical detail, all mechanistic complexities of wildfires; such a goal is, we believe, impossible to achieve. Rather, we sought to construct a model system that would enable the examination of a very important—and very specific—phenomenon relevant to wildfires: the transition of small, slowly burning fires into intense feedback-stabilized fires (2). Such simplified models are required to study natural fires in the laboratory (3).

The literature on wildfires suggests a mechanism of positive feedback between fires and the atmosphere (4, 5). Spreading fires enhance local wind speeds, which, in turn, enhance rates of spread (here, we simplify). We disagree with Sullivan and Cruz (1) that positive feedback must lead to detonation; after all, negative feedback need not lead to extinction. Positive feedback has a physical limit; it generates large fires that travel quickly at steady state until conditions change.

The transition in our system (2) is not a simple transition from laminar to turbulent flow. The "unstructured" flame changes its position on the nitrocellulose strip (e.g., it moves from the top of the strip to the bottom, and vice versa); as it does so, the flame—through a combination of thrust and buoyancy—pushes the strip in different directions. As the strip moves, the flame encounters "wind," just as someone in a moving car might encounter wind by opening a window. This wind moves the flame, completing a feedback loop that gives rise to rates of spread that are faster than those of "structured" flames.

Our analysis (2) of the convective Froude number (Fr_c^2) is distinct from analyses carried out on other systems because our system is distinct. The velocity of "wind" encountered by a flame is roughly proportional to the force that the flame exerts on the nitrocellulose; this force, in turn, is proportional to the velocity of gases within the flame. Although the meaning of precise values of Fr_c^2 (e.g., $Fr_c^2 < 1$) differs between our system and wildfires, in both systems this number represents the relative contribution of inertial and buoyant forces; we use only this representation to frame our analysis.

Our study (2) asks this question: "Do slowly spreading fires exhibit detectable symptoms of critical slowing down prior to transitioning to intense, feedback-stabilized fires?" In our model system, the answer is "yes." This finding is significant because it suggests that the onset of fast-moving, feedback-stabilized fires may have early warning signals. As we point out in our paper (2), future examinations of critical slowing down in other systems (e.g., wildfires) will require models [e.g., coupled atmosphere-fire models (6)] that more accurately capture mechanisms of feedback specific to those systems.

Jerome M. Fox[a] and George M. Whitesides[a,b,c,1]

[a]*Department of Chemistry & Chemical Biology, Harvard University, Cambridge, MA 02138;* [b]*Wyss Institute for Biologically Inspired Engineering, Harvard University, Cambridge, MA 02138; and* [c]*The Kavli Institute for Bionano Science and Technology, Harvard University, Cambridge, MA 02138*

1 Sullivan AL, Cruz MG (2015) Small-scale flame dynamics provide limited insight into wildfire behavior. *Proc Natl Acad Sci USA* 112:E4164.

2 Fox JM, Whitesides GM (2015) Warning signals for eruptive events in spreading fires. *Proc Natl Acad Sci USA* 112(8):2378–2383.

3 Finney MA, Cohen JD, McAllister SS, Jolly WM (2013) On the need for a theory of wildland fire spread. *Int J Wildland Fire* 22(1):25–36.

4 Clark TL, Jenkins MA, Coen J, Packham D (1996) A coupled atmosphere–fire model: Convective feedback on fire-line dynamics. *J Appl Meteorol* 35(6):875–901.

5 Jenkins M, Clark T, Coen J (2001) *Coupling Atmospheric and Fire Models. Forest Fires: Behavior and Ecological Effects* (Academic, San Diego), pp 257–302.

6 Coen JL, et al. (2012) WRF-fire: Coupled weather-wildland fire modeling with the weather research and forecasting model. *J Appl Meteorol Climatol* 52(1):16–38.

Author contributions: J.M.F. and G.M.W. wrote the paper.

The authors declare no conflict of interest.

[1]To whom correspondence should be addressed. Email: gwhitesides@gmwgroup.harvard.edu.