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Response

A response to comments of Cruz *et al.* on: 'The effect of ignition protocol on the spread rate of grass fires'

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The aim of Sutherland *et al.* (2020) (hereafter SSM20) was to investigate the effect of ignition protocol on the fire's development to a quasi-equilibrium rate of spread, not to directly criticise Cruz *et al.* (2015). For comparable ignition speeds, the simulations in SSM20 are in broad agreement with their experimental observations. Experiments that measure quasi-equilibrium spread rate must carefully verify that the fires are indeed properly developed. We refute the claims of Cruz *et al.* (2020*a*) (hereafter CSBG20) and show the methodology utilised by CSBG20 cannot distinguish fires in the quasi-equilibrium state from fires in the surge regime identified by SSM20.

CSBG20 take the stance that SSM20 were entirely focused on criticising Cruz *et al.* (2015). This is not the case – the purpose of SSM20s was to examine the effect of different ignition protocols on the quasi-equilibrium rate of fire spread and the time it takes for the fire to reach quasi-equilibrium. Although the simulations of SSM20 were motivated by the different ignition protocols used by Cheney *et al.* (1993) and Cruz *et al.* (2015), and the simulations were based on the C064 experiment, they did not otherwise attempt to replicate the experimental conditions (plot size, ignition line length, ignition speed, fuel load and wind speed) of Cruz *et al.* (2015). In particular, SSM20 did not conclude that the experimental design of Cruz *et al.* (2015) was inadequate. Rather, they concluded that if the intention is for the fire to reach a quasi-equilibrium state and to avoid unintended surging behaviour, then the simulations suggest that the inward ignition protocol should be avoided. The simulations also suggested that the outward ignition protocol does not produce oscillations and so may be a more prudent choice, but that an automatic ignition line with an effectively infinite ignition speed would be preferable.

Maintaining consistency in experimental design is desirable in scientific studies to ensure the results of separate studies are comparable. Where differences in design occur, it is then necessary to investigate the effects on the resulting observations. SSM20 chose to study the acceleration of a grass fire ignited by an outward ignition protocol (similar to Cheney *et al.* 1993) and an inward ignition protocol (similar to Cruz *et al.* 2015). The results of SSM20 show that, with exception of long ignition lines or slow ignition speeds, both ignition protocols tend to the same quasi-equilibrium rate of spread, R_{qe} and, with the important exception of the fastest ignition speed, R_{qe} was typically achieved within similar distances from the ignition line (~50 m on a 100-m-long plot). The fastest inward ignition speeds led to faster development to R_{qe}. As acknowledged by CSBG20, SSM20 found the faster ignition speed '*achieve*[*d*] *a quasi-equilibrium within approximately 20 m*', which is consistent with the findings of Cruz *et al.* (2015). In this specific case, the simulation and experimental results are in agreement, and the simulations of SSM20 support the experimental design used by Cruz *et al.* (2015). Because the focus of SSM20 was on the acceleration of the fire over a variety of ignition protocols, none of which exactly replicated the experimental conditions of Cruz *et al.* (2015), extensive discussion of this point was inappropriate. We maintain that interested readers can compare the simulation results with their own experimental designs with greater insight than we could provide.

CSBG20 present evidence to suggest the data of Cruz *et al.* (2015) are comparable with those of Cheney *et al.* (1993, 1998) and argue that this discounts the simulation results of SSM20. However, it is not valid to say this casts doubt on the results of SSM20, which were broadly consistent with Cruz *et al.* (2015) in the few circumstances where the simulations were similar to experiments. CSBG20 state '*contrary to the assertion of SSM20, the two datasets do not have distinctly different fire behaviour characteristics*'. The only comparison between Cheney *et al.* (1993) and Cruz *et al.* (2015) in SSM20 was to highlight that different ignition protocols were used. The comparison made by CSBG20 comparing R_{qe} from Cruz *et al.* (2015) with the model of Cheney *et al.* (1993) does not discount the possibility that individual fires were measured in the development phase, the surge phase, the 'dip' following the surge (e.g. SSM20 fig. 9), or the quasi-equilibrium phase. As no measurements of R_{qe} at high time resolution appear to exist, there is no absolutely conclusive evidence one way or the other that the fires were indeed, individually, spreading at a quasi-equilibrium rate.

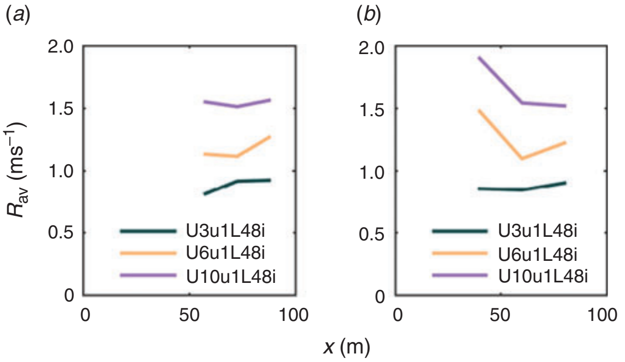

Fig. 1. (*a*) Data from SSM20 fig. 6*a*, inward ignition protocol with varying wind speed, averaged over three 15-m measurement regions in the quasi-equilibrium regime after a 50-m development region. (*b*) The same data averaged over three 20-m measurement regions after 30-m development; note that in (*b*), R_{av} is averaged when the fire is in the surge regime. The *x* (m) position is the centre of the averaging regions (see text).

CSBG20 argue the fires analysed by Cruz *et al.* (2020*b*) were in a quasi-equilibrium regime by presenting three averaged measurements of rate of spread, R_{av}, per fire (fig. 2a of CSBG20). However, this averaging process does not conclusively identify the quasi-equilibrium region. The quasi-equilibrium inward ignition protocol simulation data presented in SSM20 fig. 6a were similarly split into regions: a 50-m development region and three 15-m measurement regions (discarding the last 5 m of data) and R_{av} in each measurement region was computed. To demonstrate this technique cannot distinguish between quasi-equilibrium and non-quasi-equilibrium spread, a 30-m development region and three 20-m measurement regions (discarding the last 10 m of data) were also used; in this case, the data are averaged in the surge regime, not in the quasi-equilibrium regime. The resulting data points are shown in Fig. 1*a* and Fig. 1*b* respectively. By comparing the data in Fig. 1, it appears that the data are from quasi-equilibrium fires (the sample size is insufficient for statistical comparison) and do not reflect the fact that the data in Fig. 1*b* are from fires in the surge regime. The data are broadly similar to those presented in CSBG20 fig. 2a. Several, but not all, fires in CSBG20 fig. 2a have the maximum value at the first point, suggesting some fires may have been initially measured in the surge regime. Only highly time-resolved data (i.e. more than three points) are sufficient to show the time series of *R* is statistically stationary.

CSBG20s claim that '*As a population, fires were not accelerating or decelerating once they passed the first interval marker at 19 m from the ignition line*' (*Cruz et al.* 2020*a*) is a poor justification that each individual fire spreads at a quasi-equilibrium rate. The population involves different fuel treatments and wind speeds, and therefore, the individual fires may develop at different rates; thus, considering the population as a whole may obscure the development of individual fires to a quasi-equilibrium rate.

CSBG20 broadly claim that little comparison between the simulations of SSM20 and experimental results was made. The simulation methodology employed by SSM20 was validated in previous studies (Moinuddin *et al.* 2018) against the well-known results of Cheney *et al.* (1993). SSM20 can be considered an extension of Moinuddin *et al.* (2018), where parameters (ignition line, speed and direction) are varied independently in accordance with the scientific method. The simulated fire spread for the inward ignition protocol in SSM20 is consistent, as far as is comparable, with the experimental observations of Raposo *et al.* (2018) and Hilton *et al.* (2016, 2018), which all use the data of Cruz *et al.* (2015). The pattern of flaming exhibited in fig. 2 (Plot 34) of Cruz *et al.* (2015), i.e. the slightly concave head and region of deep flaming in the centre of the plot, is consistent with the inward ignition simulations in the surge phase. Results from Cruz *et al.* (2015) were used by Hilton *et al.* (2018), who demonstrated that a dynamic, i.e. non-quasi-steady, model was required to capture the evolution of the fire front. Images shown by Hilton *et al.* (2016) also show the concave head fire and deep flaming in the centre of the plot similar to results presented by SSM20.

CSBG20 claim that the simulations use artificial constant wind and that the input wind field is not dynamic. It is important to clarify that, although the boundary condition far from the fire uses a wind profile that varies only with height, turbulent wind fields develop throughout the domain, in contrast to many operational or reduced fire spread models (e.g. Hilton *et al.* 2018), which use non-turbulent wind fields, or wind fields that are completely uniform in space. SSM20 dedicate the section *Wind field development and its effect on fire spread* to discussion of this important feature of the simulations. CSBG20 also claim that '*The variation in rate of fire spread observed in Fig 2*a *is best explained as being a function of the random variation in wind speed*.' However, because no evidence of how the fires respond to turbulent fluctuations is presented, the claim that this is '*the best*' explanation is unsupported.

Finally, CSBG20 question the similarities in the results of Mell *et al.* (2007), Moinuddin *et al.* (2018) and SSM20, which exist despite differences in grid resolution. The separate studies used different versions of the WildFire-urban interface Fire Dynamics Simulator (WFDS) model, different submodels and parameter values, and Mell *et al.* (2007) did not consider grid convergence owing to computational restrictions. Mell *et al.* (2007) instead chose to use a resolution that adequately reproduced large-scale plume features. Moinuddin *et al.* (2018) and SSM20 chose to use a resolution that provided more rigorous grid-converged results.

Conflicts of interest

The authors declare no conflicts of interest.

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