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New Zealand field-scale fire experiments to test convective heat transfer in wildland fires

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Introduction

Wildfire physics has traditionally been studied through intensive modelling that requires numerous assumptions of combustion and heat transfer (Sullivan 2009) adapted from established structure-fire engineering relations. Renewed emphasis in experimental research has caused rethinking of some of the most basic concepts in wildland fuel particle ignition and flame spread. New findings from laboratory experiments conducted by the U.S. Forest Service's Missoula Fire Sciences Lab reveal the source of convective heating in spreading fires derives from fire-induced vorticity, which forces flames downward and ahead of the combustion zone in intermittent contact with fuel particles (Finney et al. 2015). New laboratory techniques capture the intermittency and suggest it has predictable average frequencies familiar in studies of buoyant instabilities. The scaling relations for wind and buoyancy have shown promise at field scales but need to be further tested.

A project being led by Scion's Rural Fire Research Group in New Zealand aims to test this hypothesis that heat-driven buoyancy (convection) creates a series of peaks and troughs in the flame front that drive fire spread and scale with flame size and wind speed. The theory is being tested through a series of heavily-instrumented fire experiments at sites in a range of fuel types, starting in uniform crop stubble fuels (February 2018), moving to more complex scrub fuels (2019/20) and then to wilding pine forest fuels (2020/21).

Methods and Instrumentation

In the first phase of the experiments, nine approx. 2 hectare burn plots were established near Darfield, New Zealand to measure atmospheric turbulence structure and scales, heat transfer, and flame characteristics on spreading line-fires in cereal crops (Figure 1a) (Finney et al. 2018). Loading and particle sizes were measured in the fields of harvested wheat, barley, and triticale crops. These crop stubble fuels, with their even row spacings and uniform cut height, provide the best real-world approximation of the laser-cut cardboard fuel arrays used in the laboratory experiments. Field burning was carried out during March 2018. Fires were ignited with drip torches from multiple line segments along the upwind edge to allow a linear flame zone to develop and spread across the plot under the prevailing wind (Figure 1b).

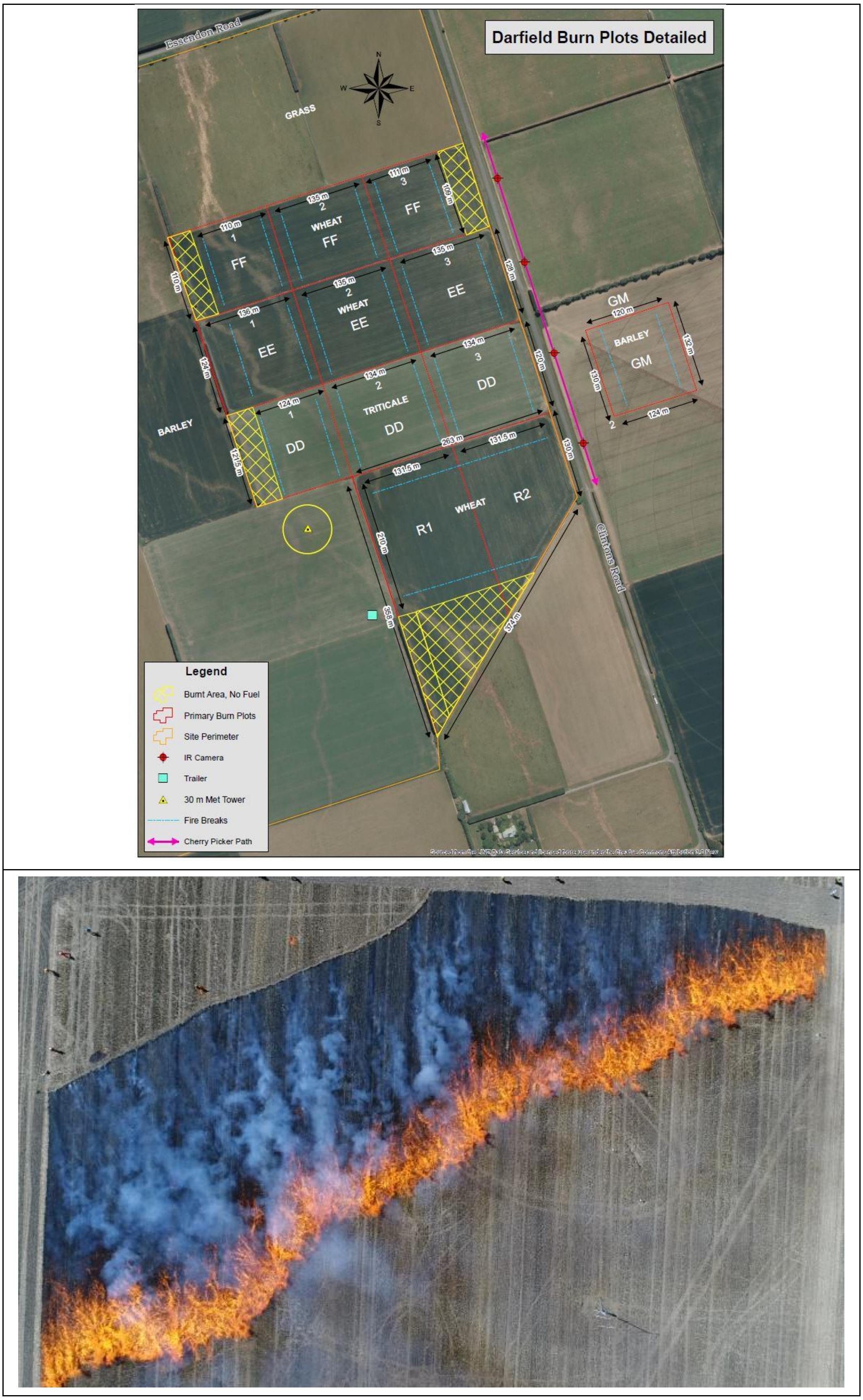

Figure 1. (a) Aerial image of experimental burn plots in cut cereal crops in Darfield, New Zealand; (b) linear flame zone spreading from simultaneous line ignitions along a fire break.

Experimental design focussed on measuring a cascade of spatial and temporal scales starting from the fuel bed, through the flame and up to a few hundred meters in the atmosphere. Air turbulence and temperature characteristics as the fire passed were measured by a 10 metre tower near the centre of each plot with sonic anemometers at 2m, 5m, and 10m along with an array of 20 thermocouples installed at intervals along the vertical pole (Figure 2a). A 30m sonic anemometer tower was set up outside the fire perimeter to measure the near-surface atmospheric background turbulence structure. Instruments to measure heat fluxes and flame behaviours were installed at intervals along 30m lines oriented parallel with the anticipated wind direction. These sensor packages consisted of a heat flux package with tri-directional differential pressure disks to measure air and flame velocity (Grumstrup et al., 2018), fine wire thermocouples (bead $5e^{-5}$m) for gas temperature, and a wide-angle radiometer (Figure 2b). Frequency and distance of forward flame bursts were measured using 5m horizontal arrays of fine-wire thermocouples each separated by 0.2m (Figure 2c). Changes in hydrostatic atmospheric pressure were measured using a pressure transducer with the orifice flush with a steel plate positioned on the ground (Figure 2d). This package also measured flame residence time with a flame ionization probe that only records changes in electrical conductivity from ionization when immersed by flame. A series of in-fire cameras were also installed to record passage of flame zones (60 frames per second) through the instrument arrays (Figures 2e & 3a). All of these instrument packages used a custom-built 8-channel data logger (Figure 2f) recording at 50Hz which synchronized time-stamps and sensor location with an on-board GPS unit.

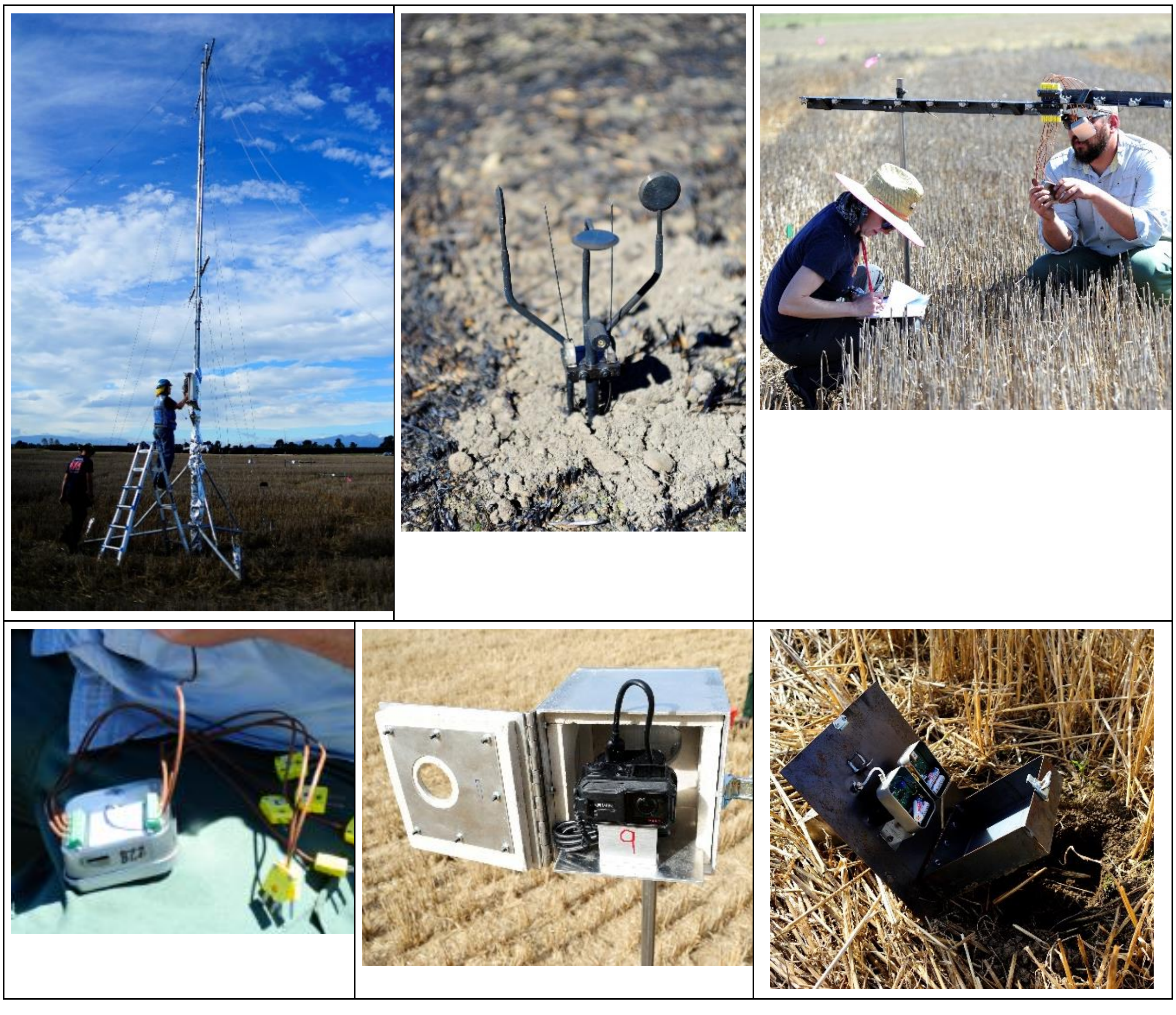

Figure 2. Pictures of field instrumentation (clockwise from top left): (a) 10m tower with sonic anemometers and vertical array of fine-wire thermocouples; (b) heat flux sensor with tri-directional velocity disks, radiometer and thermocouples; (c) horizontal array of fine-wire thermocouples, (d) hydrostatic pressure and flame ionization detector; (e) in-fire video cameras; and (f) custom 8-channel data logger with GPS.

Remote sensing of the burn experiments was accomplished using a variety of tools. A Doppler LIDAR unit with 18m resolution (Halo Photonics, Streamline 75) was used to scan horizontal and vertical swaths of wind velocity (Figure 3a), while a SODAR was continuously measuring the velocity boundary layer up to 300m AGL. Three high-speed longwave infrared cameras mounted on a 20m portable lift recorded oblique video of fire spread, as well as pre-fire and post-fire thermal features of the airflow across the fields; this included a high resolution Telops FAST IR camera (https://telops.com/products/high-speed-cameras) (Figure 3b). A fixed-wing unmanned aerial vehicle (UAV) (Figure 3c) flying pre-programmed traverses was used to capture changes in atmospheric turbulence before, during and after the fires. Aerial video was recorded from two quadcopter UAVs flying overhead and obliquely to the experimental plots (Figure 3e). High-speed thermal video was recorded of the fires from a ground-based camera (FLIR 6811) at 480fps and standard video (240 fps, 700fps) from multiple angles (Figure 3d).

Figure 3. Remote sensing instrumentation (clockwise from top left): (a) scanning Doppler LIDAR; (b) cherrypicker-mounted IR camera; (c) fixed-wing drone with turbulence probe; and (d) still image from in-fire video camera, (e) side-on view from high-speed FLIR camera, and (f) overhead UAV image showing peak-and-trough flame structure consistent with buoyant instabilities of the flame zone.

Preliminary Findings

All fires occurred with 10m winds of approximately 6 to 10 m s^{-1}. With different fuel species (wheat, barley, triticale), wind, and fuel moisture, fire rate of spread among plots varied from about 40 $m.min^{-1}$ to over 100 m min^{-1}, with flame lengths of approximately 1m to 5m. Forecasted wind direction was accurate to within about 10 degrees and used to orient directionally-dependent instruments (thermocouple arrays, heat flux packages) with the expected spread direction.

Preliminary observations and examination of the data suggest these field-scale stubble fires were consistent with laboratory results that convective heating plays the crucial role in heating fuel particles to ignition in wind-driven wildland flame spread. In-fire and high-speed IR video (Figures 3d & 3e) revealed intermittent flame bursts contacting fuel particles 1 to 5 metres forward of the ignition interface. No pyrolysis products were visible ahead of the flame zone before flame contacts occurred. Coherency of the flame burst parcels was evidenced from synchronous spikes in temperature among thermocouples extending in a line forward of the flame zone (Figure 4a). Flame residence time was approximately 10 seconds as estimated from video as well as the ionization detectors (Figure 4b).

Results from the analysis of fire turbulence in front of, within and behind the spreading flame front, using the 10m tower sonic anemometer and thermocouple data, and longwave infrared camera imagery, are reported elsewhere in this conference proceedings (Katurji et al. 2019).

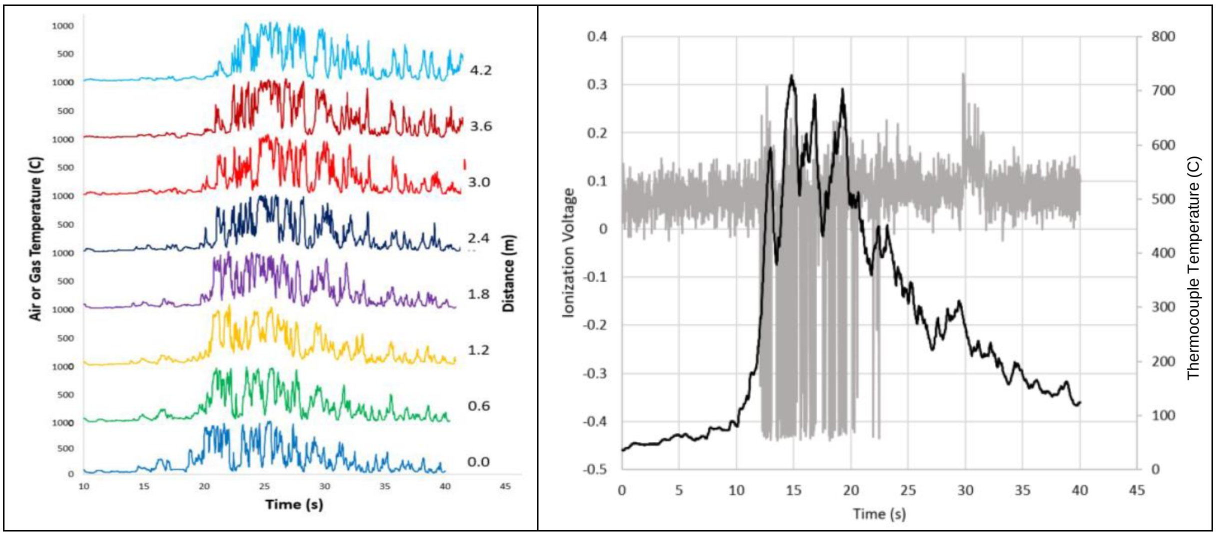

Figure 4. (a) Coherency of temperature data from 4.8m long thermocouple array for plot DD2 (spread rate ~100m min^{-1}); and (b) example of flame residence time estimated at about 10s from plot EE3 shown relative to medium-fine $1e^{-4}$m diameter thermocouple temperature.

Future Work

Full analysis of all data is still required to confirm convective heating characteristics associated with these stubble fires. Future field research will entail application of these experimental methods to more complex fuel types to test scaling of heat transfer in fires with larger flames, including crown fires. Work has begun on establishing the research sites for these next stages of the research. These include burns in gorse scrub fuels (in the Rakaia Gorge) scheduled for Oct/Nov. 2019, and in dense wilding conifer stands (near Lake Pukaki) for Oct/Nov. 2020.

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