Improving management of UK wildfire through knowledge exchange

Understanding fire intensity and severity: Implications for managing wildfire and prescribed fire

Report

2nd wildfire@manchester seminar, 13th June 2013

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Professor John Dold (University of Manchester)

Discussants:
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George Winn-Darley (Moorland Association)

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Slides:
The report is intended to be read alongside the keynote presentation slides which are included at the end of this report. A separate pdf version of these slides as well as this report are available to download from www.kfwf.org.uk

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1. Introduction

1.1 The KfWF Project

Julia McMorrow, Senior Lecturer in Remote Sensing at the School of Environment, Education and Development (SEED) and NERC Knowledge Exchange Fellow for the Knowledge for Wildfire (KfWf) Project, introduced the second seminar. KfWf is a two year NERC funded project. Contact details for the project are:

Website: www.kfwf.org.uk
Twitter: @kfwf_manchester

Gareth Clay, Lecturer in Physical Geography at SED, ran a live Twitter feed during the session, presenting questions and feedback as it came in.

1.2 Wildfire 2013

One of the aims of the KfWf Project is to help organise knowledge exchange events on UK wildfire issues. There will be a KfWf session at the Wildfire 2013 Conference, which is being held 22nd – 23rd October at the Vale Resort, Hensol, near Cardiff. Further details can be found at: http://www.ruraldevelopment.org.uk/wildfire/

1.3 Dedication to Sean Prendergast

The seminar was dedicated to Sean Prendergast, who sadly passed away recently. Sean was Head of Field Services at the Peak District National Park. His pioneering work with the Park's Fire Operations Group helped to kick start knowledge exchange on UK wildfire.

1.4 Programme

The seminar consists of 3 parts:
- Keynote speaker, Professor John Dold, School of Mathematics, University of Manchester
- Invited responses from Andy Elliott, Dorset Fire and Rescue Service and George Winn-Darley from the Moorland Association
- Open discussion for all attendees to share their views

A wine reception followed to continue networking and discussion.

1.5 Introduction to keynote speaker

John Dold is Emeritus Professor in Mathematics at The University of Manchester. He has worked as a physical scientist on combustion-related research issues for over 35 years. He works as a wildfire consultant in the UK and abroad, helping to develop new operational wildfire control techniques and methods of active wildfire monitoring and analysis. John is involved in training and wildfire public awareness work, and especially in laboratory studies of wildfire and atmospheric interaction modelling and simulation. He conducts experimental field burns; and has organised three field burn exercises in the UK, with some of the academics and fire service practitioners here today being part of these exercises. John serves with Julia on the England and Wales Wildfire Forum and the Research and the Information work stream of the Chief Fire Officers' Association Wildfire Group.

2. Keynote John Dold: Understanding fire intensity and severity

John invited the audience to ask questions during the presentation. A pdf version of the slides are available to download from www.kfwf.org.uk

2.1 Slide 1: Title slide

The talk is about two concepts. The first, fire intensity appears to be relatively easy to understand, yet there are areas of difficulty when one delves deeper. The second, 'severity' tends to be used loosely, resulting in confusion. The talk goes beyond John's main area of expertise in fire intensity to open up the wider debate about fire/burn 'severity'. It aims to raise questions and encourage discussion.

2.2 Slide 2: Two terms often used for bushfires or wildfires

The background photo shows a group of scientists on the moors in the rain – conditions very far from fire weather. Sean Prendergast is on the left hand side. He organised a fantastic day for the fire scientists in this photograph. Sean was described as a great facilitator; who was quick at picking up on ideas, running with them and implementing them; a man who will be sorely missed by those who got to know him well.

Intensity is usually linked to **'fireline intensity'**; the rate of energy release (that is, the 'power') behind any metre of fire front, measured in kW or MW per metre. Some people question whether intensity is the right word. John agreed with the definition and term, and pointed to the analogy with light intensity.

Byram in the 1950s presented a formula which gives the intensity for a steadily advancing line fire. If the fire is advancing smoothly and steadily with a long front then Byram's formula applies. However, the formula does not apply if the fire is a crooked shape, or is behaving in an unsteady way; *i.e.* speeding up or slowing down. In such circumstances you cannot readily use Byram's formula. So, although fire intensity is an accepted physical concept of power per unit length, what does it actually mean in practice for a real wildfire?

The next concept, 'severity', is less clear cut. The Met Office use the term in their Fire Severity Index (FSI). 'Severity' can have different and possibly conflicting interpretations, depending on the aspect of fire management concerned. For instance:

- *Difficulty* of suppression. Severity here implies severe fire behaviour which makes it hard to put out, or hard to escape from if it is travelling towards you; fires which tend to result in large fire scars and which underpin the concept of the Met Office FSI.
- *Damage* – impact produced by the fire; the direct effect on vegetation and soil and what you see immediately the fire has gone.

Are these two meanings consistent? Perhaps in some respects, but certainly not in others. What links would we expect between intensity and severity in all of their different ramifications?

2.3 Slide 3: Outline of the presentation

Basic meaning of fireline intensity: For a straight, steadily-spreading fire, there are three essential elements of intensity: (i) the energy released during the combustion; (ii) the degree and efficiency of the burning; and (iii) the rate or speed of burning.

However, for irregularly shaped fires, or fires behaving in an irregular way, John proposed a ***plot-based line fire equivalent intensity*** (he asked for suggestions of a better name). The challenge is measuring it meaningfully. The motivation for doing so is fire control, safety and habitat management. He suggested a geometrical approach for measuring ***'line fire equivalent' intensity.*** He gave an example of a particular ignition pattern and the resulting irregular shape of fire front and flaming region. Interpretation of the line fire equivalent intensity itself is another question, as there are still experimental and conceptual ideas which need to be put together.

2.4 Slide 4: First, some comments on Severity.

The slide showed a burnt tree and the audience were asked: When the tree burned, was it an intense fire or not? And was it a severe fire or not? Two possible ways of looking at this are:

Burn Severity – the effect of the fire on vegetation and soil. Specifically, this includes: (i) the degree of impact on above ground vegetation (how much vegetation is burnt off, which may or may not be a temporary impact); (ii) the amount of permanent damage done (root damage and plant-kill); (iii) the degree of damage to the seed bank and the possibility for post-fire regeneration; and (iv) how much loss of soil there is (burning of peat and humus, or by soil erosion). Burn off may be the objective in habitat management. So too is plant kill if fire is being used to remove an invasive species and encourage re-colonisation by a different species. The other effects we usually wish to avoid. Burn severity can be used to describe different outcomes in controlled fires, provided that they are planned and executed well.

Fire Severity **–** This is connected with the idea of difficulty in controlling fire behaviour, or how hard is it to suppress and manage. Fire danger rating systems and the Met Office FSI use parameters such as current and past weather, soil and transpiration of the vegetation to predict what they consider to be fire severity. For some countries, FSI is based on extensive data and analysis. In the UK, some calibration was done originally by the Met Office and Natural England but a lot more needs to be done in terms of making the FSI into a concept which is more widely understood and gives meaning to the different levels of fire severity, not just for the originally intended purpose of deciding when to close Access Land, especially on moorlands.

What, therefore, are the links between fire intensity and severity? John was not giving answers but wanting to raise discussion around this relationship.

2.5 Slide 5: Basics of intensity – the burning process itself

How does fire convert vegetation into energy? John gave the example of a sheet of paper (processed wood pulp) to demonstrate fast and slow pyrolysis. He showed a video clip of an experiment where a piece of paper is put into a toaster and soon grey and white smoke is produced (vapour), along with 'black stuff' (carbon).

Plant growth and pyrolysis: Plants use sunlight, CO_2 and water to synthesise glucose-type molecules. They then polymerise these molecules by knocking off one water molecule, repeating this until eventually long chains of cellulose $(C_6H_{10}O_5)_n$ and other molecules are formed. Cellulose production is inherent in plant growth.

If we take cellulose (as in a sheet of paper) and heat it to temperatures of 200°C to 300°C, we get a process of *slow pyrolysis* – a chemical reaction which drives off water molecules and leaves mainly black carbon.

If cellulose is heated further to about 350°C or more, another reaction predominates, one which is much faster at higher temperatures than the slow pyrolysis (which still takes place). Fast pyrolysis rips apart the cellulose and turns it into a group of molecules which are driven off as vapour, for instance, levoglucosan ($C_6H_{10}O_5$). If this vapour is mixed with oxygen at a high enough temperature (650°C or more), flames can be produced – *flaming combustion*. If the vapour does not burn, it forms a white smoke.

Some plants also contain oils and fats and components that vaporise at lower temperatures than 250°C to 350°C. These tend to be driven off earlier and are more energetic in their burning.

If the char formed by slow pyrolysis becomes hot enough, it can burn on the surface by the further process of *surface smouldering*.

2.6 Slide 6: Basics of intensity – What is the degree of burn?

If we take vegetation and heat it up, we get: flammable vapour which releases energy if it achieves the right conditions to actually burn (mixing with oxygen at a high enough temperature) but if these conditions are not achieved then unburnt vapour remains (so that energy is not released); some unburnt vegetation (energy not released); some char which can smoulder on the surface if it is hot enough (energy released) and some that remains unburnt if its temperature is too low (energy not released). Finally, non-flammable ash can also be produced (energy not released).

The degree of burning will therefore be less than 100% if there is any unburnt vegetation, unburnt char (black residue), ash (inert residue), unburnt vapour (white smoke), or incompletely burnt vapour (black smoke). The first three can all be measured. It is harder to quantify the other two. For unburnt vapour we need to measure how much white smoke there is. For incompletely burnt vapour (flames that partly burn but then go out) we need to quantify the black smoke. Black smoke means there has been combustion, but it is incomplete. These all contribute to less than 100% efficiency in the burn process.

Example: Take a receptacle and burn vegetation in it (demonstrated using a short video of newspaper in a metal foil container). You know how much vegetation (newspaper) was available to burn from weighing it unburnt, and you can time it to see how long it takes to burn (28s). There was a stage of active burning, with almost no smoke so that the combustion was very efficient in this example. There were lots of red areas inside the char near the end, showing surface combustion. You are then left with a residue of mainly carbon fragments, which you can weigh to find the difference from the starting weight. Inside the receptacle there are condensed residues of unburnt volatile (pyrolysis) products which weigh relatively little. Putting the measurements together we get:

- Mass of unburnt paper: 8.83g
- Total mass of the residue: 0.60g
- Mass condensed in the pan: 0.06g
- Time of burning: 28s

What mass of paper actually burnt? What was the average power generated? The next slide will help to answer these questions

2.7 Slide 7: Energy of combustion

The chemical formula used to represent cellulose, $C_6H_{10}O_5$, is one of the monomers in a chain of cellulose. From the formula you can figure out how many oxygen molecules are needed to turn this into CO_2 and water H_2O (in this case six). The molecular weights of the two (in atomic mass units) are

- One cellulose monomer $C_6H_{10}O_5$: 162
- Six oxygen molecules $6O_2$: 192

A rule of thumb that can be used to calculate the energy released in this chemical reaction is one that is based on oxygen calorimetry (Drysdale). Essentially, the energy of burning is about 14 kJ/gm of O_2 consumed. You don't have to know what the fuel is, just the amount of O_2 consumed.

1g O_2 → 14 kJ of energy
1kg O_2 → 14 MJ of energy

To calculate how many grams of cellulose are consumed, 192g of oxygen burns 162g of cellulose, so 1g of oxygen consumes 162/192 g of cellulose.

So the energy released per gram of cellulose burnt is

$$Q = 14 \times (192/162) \text{ kJ per gram of } C_6H_{10}O_5 \text{ consumed,}$$

$$Q = 16.6 \text{ kJ per gram of } C_6H_{10}O_5 \text{ consumed}$$

Roughly speaking, you need to burn 60g of cellulose to produce up to 1 MJ of energy. A MJ is quite a lot of energy; it equates to burning about 12 sheets of A4 paper, or about 8 heaped teaspoons of sugar or flour

Also, about 27g of pure carbon produces 1 MJ by a similar calculation. Exactly the same technique is used for real vegetation with, for example, about 52g of $C_6H_9O_4$ (typical of wood) burning to produce 1 MJ.

How does moisture effect this calculation? (*question from audience*): Moisture does effect the calculation, but not by a lot. The amount of energy needed to remove the water is relatively small compared to the amount of energy released during combustion, with 1 MJ able to boil away more than 400g of water. If there is too much water content (usually more than about 30% to 100% of dry mass, depending on the vegetation type) it is not going to burn anyway.

2.8 Slide 8: Fireline intensity of a straight steady fire

Imagine you have an ideal fire, moving in a straight line, spreading from right to left on the diagram at a steady rate through a plot, to leave black residue:

Where:

its rate of spread is R m/s

the fuel load consumed is m kg/m^2
(reducing m from the total fuel available if less than 100% burning)

burning at an energy of Q MJ/kg

If we put these elements together in Byram's 1st formula we get the power per length of the fire which is being generated, or *fireline intensity*:

$$I = Q\,m\,R$$

So fireline intensity increases for: faster spread (R), higher fuel load consumed (m) and more complete combustion which turns more of the fuel available into energy, effectively increasing the value of m to be used in the calculation. The value of Q in this formula depends on the vegetation type and so does not vary unless the fire moves from one vegetation type into another. But even then, its value typically does not vary much between common types of vegetation.

Another way of looking at it, which Byram also identified, can make use of ***flame residence time*** (t_b). If the fuel burns for a certain period (the flame residence time), while the flames are advancing at a spread rate (R), we get the distance travelled in this time, known as the ***flame depth*** (d). The diagram shows the flame depth as the width of the flaming fire front in both plan and elevation view. Thus the flame depth is given by the equation

$$d = R\,t_b$$

Rearranging this equation, the spread rate is the flame depth divided by the flame residence time:

$$R = d / t_b$$

If we now use this equation to substitute for R in Byram's original formula we get **Byram's 2nd formula** (not written in Byram's original notation):

$$I = Q\, m\, d / t_b$$

So fireline intensity (I) increases for: a higher fuel load consumed (m), more complete combustion (which increases the effective value of m), a shorter flame residence time (t_b) and a greater flame depth d.

What about the size of the fuel? (*question from the audience*): Factors such as this affect the spread rate of the fire R and the flame residence time t_b while the formulae remain the same. Fuel size can affect how long the burn lasts; for instance, a mixture of light and large fuels together, could produce a longer flame residence time if both components burn. If only the lighter fuels burn, then the larger fuels must be subtracted from the fuel load consumed. It's important to realise that fuel load here is only that part of the vegetation which turns into flames. Byram's two formulae are looking at broad overview concepts that allow for many variations of detail; these details, of how exactly the fire burns, is a much greater issue and many aspects of it are still not fully understood.

2.9 Slide 9: Intensity of irregular, unsteady firelines – a plot-based approach

The motivation for developing an alterative to a steady, line-based approach is illustrated by the kind of spiral fire shown in the photograph and video clip. They are from recent work in South Africa (June 2012). The helicopter is flying in a spiral from the centre outwards, dropping little capsules which ignite after 30-40 seconds. There is intense burning initially in the middle of the plot. Later ignitions in the outer areas create flames that are pulled in towards the centre, also burning intensely. The combined effect is a complex fire front that burns most of the plot in a much shorter time than a simple line fire would have done. A strong convection column, pulls in flames from everywhere else and helps to drive the flame spread within the plot. Quite soon it is burnt out and the fire evidently burnt intensely. But what is the intensity of such fires as this?

This was not a wildfire, but irregular shapes are typical of wildfires. Patterned ignition (as here) can create many other fireline shapes. Wildfires are rarely straight, so Byram's first formula does not apply in practice for these non-linear fire events. If you have spotting (random and scattered ignition points), it can produce a lot of interactive fires. Again, what is the intensity of those fires? The key question is: What formula do we have to calculate intensity for these real situations?

John proposed a ***Geometrical approach***. The left-hand side of the diagram on the slide illustrates an actively flaming region that is strongly curved and even disjoint, in a square plot of area A m^2 with length and width L m.

Imagine taking all of these flaming areas and shifting them to make a single linear fire front of equivalent area across the plot, as sketched on the right. The aim is to geometrically change the shape into an equivalent simple linear fire front, having the same actively flaming area, so that Byram's formula can be applied.

The resulting flame depth (d) can now be measured geometrically from the diagram, or calculated as the width of the plot (L) multiplied by the proportion of the plot area (A) which is flaming (a):

$$d = L \times a / A$$

We can now apply Byram's formula to calculate fire intensity, but for a non-straight fire. We can refer to this as the ***'plot-based line-fire equivalent' (PLFE) intensity*** (J):

$$J = Q\, m\, d / t_b$$

Or substituting for d in this equation, as calculated above:

$$J = (Q\, m\, L / t_b) \times a / A$$

Thus PLFE intensity increases if the flaming area a, within the plot is increased.

2.10 Slide 10: Intensity of irregular, unsteady firelines – example of a plot-based approach

As an example of the PLFE approach in practice, John showed a video clip of a patterned ignition of a 4 hectare plot (200m x 200m), which had been prepared with fire breaks. This time the helicopter flew in a spiral from the outside inwards. The results are captured as thermal infrared images.

The flames are initially wind-driven while the ignitions in the middle had not yet developed. The video shows a vertical feature emerging as the fire develops, with raised temperature values reaching at least 100m high. This is a fire whirl or vortex, which is part of the convection column. The base of the vortex is soon burnt out so that very hot air does not enter it, but it soon becomes visible again when it moves into the middle of the plot. The movie demonstrates how the convection of the fire is pulling the flames inwards, helping to intensify the fire.

We want to use this data to measure the fire intensity in the plot. We can do this by looking at the thermal infrared images and choosing a threshold temperature, in this case 300°C to represent the onset of *active flaming.* Flame residence time (t_b) can be measured from the image sequence. This then allows calculation of plot-based line-fire equivalent intensity (PLFE intensity) based on the proportion of the area of the plot a/A that was actively flaming at any time.

As the fire developed, a graph shows how this PLFE intensity (J) increased to exceed 24 MW/m and decreased again over a period of about 1 to 2 minutes.

2.11 Slide 11; Intensity of irregular, unsteady firelines – interpretation and next steps

The implications of the PLFE concept are that:

(i) It extends the meaning of Byram's fireline intensity (I) into situations where his formula cannot be applied.
(ii) It equals Byam's fireline intensity for a straight steady line fire, $I = J$.
(iii) It measures increased fire activity over an <u>area</u>, within which there can be: interaction between nearby flaming regions; strong convection processes, creating convection columns that may include such things as fire whirls; greater flame heights and thicknesses, increased emissivity (hence radiation); and possibly enhanced burn severity (although this has yet to be tested).

The next step is to improve the formula so that it is not plot-based; *i.e*. Line fire equivalent rather than plot-based line fire equivalent. You could, for instance, examine different parts of the plot and different values of L. Secondly, field tests are scheduled to examine the effects on woody vegetation.

2.12 Slide 12: Fire / Burn Severity and Intensity

The following possible interpretations are put forward here for discussion:

'Fire severity' as difficulty in suppression
Burn severity as damage to vegetation observed immediately after the fire
Intensity as Line Fire Equivalent Intensity

Fire severity and intensity seem to be talking about the same thing, although the term 'fire severity' is more qualitative.

In considering burn severity, vegetation damage should be related to the heat absorbed. Specifically, higher burn severity would be expected with:

- Exposure to higher temperatures and radiation; how hot the surrounding flames are and how much radiation is absorbed
- Fuel characteristics; size of the stems and leaves (thicker types of fuel, would need longer to heat up), its moisture content, conductivity, etc.
- Very important, is duration of exposure to elevated temperature and radiation.

A high fire intensity could increase the first one of these, but a slow fire (lower intensity) might increase the last if it results in a longer flame residence time t_b. Either of these could, potentially, result in an increased burn severity.

Descriptions like 'hot' and 'cold' burns therefore miss the point, as both temperature and *time* are needed, while the words 'hot' and 'cold' are descriptions of temperature alone. Moreover, the flames of a lower intensity fire do not burn at a lower temperature, while a highly intense fire (with flames of a similar temperature) may be brief and result in less vegetation damage.

Vegetal soil (peat soil) is unlikely to suffer much from a short-lived intense fire since it would absorb relatively little heat directly from the fire. The greatest damage would result if a slow (very low intensity) smouldering fire were ignited.

2.13 Slide 13: Thermocouple Temperature Measurements.

A concept of **'*thermal dose*'** is introduced to combine the joint effect of heat and time, as this is likely to affect severity, e.g. the total time multiplied by the temperature rise at a given height in the vegetation or soil.

The experiments in South Africa used thermocouple columns (thermocouples at different heights) to calculate the thermal dose above a threshold, in this case 70°C, at each height. Graphs like the one on the slide show temperature recorded over time for thermocouples at different heights above the ground. They allow the 'thermal dose above 70°C' to be calculated. The highest dose in these experiments (which involved a significant load of dead moribund grass) is found close to the ground, but its magnitude and variation with height differ between locations of the columns in any test and between test-plots. The data has not yet been fully analysed. Further tests with different vegetation will be done in July and August.

2.14 Slide 14: Summary

Intensity:

- The definition for steady line-fires has been extended to irregular fire patterns in plots (PLFE intensity)
- Consistent ways to remove the restriction to plots are being developed
- Patterned ignition can greatly enhance intensity. This can be used to suit the habitat management objective. In the South African fires, intense fire is required to remove invasive species and patterned ignition offers a way of achieving this without compromising safety.

Severity: is often used loosely. It has two distinct meanings in popular usage: *'difficulty'* in the sense that a severe fire is one which is difficult and dangerous to control, and *'damage'* done to vegetation and soil, as in 'Burn severity'.

- o Difficulty: ('Fire Severity') should correlate with the more precise term Fire Intensity.
- o Damage: (Burn Severity) is very multifaceted
  - Temperature rise and time **together** cause damage
  - Time must be included because it determines how deeply the heat penetrates into any vegetal sample, so 'larger' vegetal components take longer to heat up internally
  - High intensity fire should damage elevated fuels more (depending on plant species, condition of the species, structure, etc.) so one should also specify the fuel layer.

Ongoing tests will help to clarify Intensity-Severity linkages for some vegetation types.

2.15 Slide 15: Major questions

- What is a better catchier name for PLFE or LFE Intensity?

- Can we, and should we, define severity more tightly? Does it mean difficulty/danger or damage?
- Can patterned ignition be used to 'design' a burn to achieve vegetation objectives? Does it have a role in habitat management?

John Dold acknowledged those involved in the experiments described: Winston Trollope, Lynne Trollope, Bob Connolly and Chris de Bruno Austin of Working on Fire International; LD van Essen at the University of Pretoria; Ross Goode of Phinda Game Reserve, South Africa; and FireLab Ltd.

3. Responses from invited discussants

3.1 Andy Elliott: Station Commander, Dorset Fire and Rescue Service, Response from a Firefighter's perspective

'As a firefighter, I firstly wanted to examine what my colleagues understood by the terms fire intensity and fire severity, so I asked a few:

'Our Media Officer said "Intensity is how hot the fire is and severity is how much damage it does".

'One of our Flexi Duty Station Officers said "Intensity equals the rate of burning during the event and severity is the magnitude of the resultant damage after the event".

'I spoke to another seven firefighters and they all came up with very similar definitions, but none of those asked picked up on the subtleties within severity that John has highlighted i.e. severe meaning damaging as well as severe meaning requiring more effort to bring under control.

'In general terms, when asked for a definition, firefighters seem to be on the right lines, but my experience is that, in the field, they often confuse the two terms and see them simply as descriptive words where severe and intense take on the same meaning. It would appear that the collective works of Byram, Rothermel, Deeming, Dold etc. have little direct significance to them; or do they?

'John demonstrates, via Byram, that fire intensity will increase if the rate of spread increases, if the fuel load increases or when combustion is more complete. This is useful information for a firefighter as it can be observed on the fire ground. For example, if the wind or slope increases, then the rate of spread increases, as does the intensity. More importantly, to an Incident Commander, they will be able to predict that the fire's intensity, and therefore the difficulty to extinguish it, will increase if stronger winds, for example, are forecast. Of course, changes in fuel load can also be observed as can the likelihood of more complete combustion, when fuels become exposed to curing by the wind and sun. Therefore, these potential impacts on fire intensity can be predicted by firefighters on the ground with relatively little training or experience. In fact, this approach aligns itself very neatly with the version of Wildfire Prediction that is currently being incorporated into the new Wildfire Operational Guidance document. The factors of alignment; wind, slope and aspect are key to predicting wildfire behaviour.

‘More interesting are John’s observations of irregular, unsteady fire lines (Line Fire Equivalent) and his suggestion that an understanding of the relationship between difficulty in suppression and line fire equivalent intensity will correlate with fire severity. In all but the largest of UK wildfires, the fireline is anything but straight or regular. An understanding of this Line Fire Equivalent may help firefighters determine how dangerous or difficult to extinguish a wildfire may be, particularly in complex fires. We must remember that the experimental burns were artificially and intentionally complex. It would be useful to see how closely these match a typical UK wildfire, if there is such a thing. Perhaps more importantly for firefighters is the observation that a rapidly moving, high intensity fire may be difficult to suppress, but may not be particularly severe, yet the slower moving, less intense fire may actually be the most severe [in terms of damage done to vegetation and soil]. How can firefighters make use of this information?

‘At present, the firefighter who is untrained in wildfire is most likely to make for the biggest flames and to do their best to knock them down. One can only assume that this is an attempt to minimise the spread, and therefore severity of the fire – severity here [is] used to describe the spatial extent of the burnt area. This approach has little regard for safety and will often allow the less intense flank and tail fires to burn unchecked. Once the crews have recovered from their exertions and exposure to the intense head fire, they will of course tackle them, unaware of the damage they [the flank and tail fires] have caused. The Upton heath fire of June 9th 2011 is an example of this. Thirty pumps attended at the height of the blaze, all directed to control the rapidly spreading head fire. This was seen as important as the fire was heading directly towards a housing estate. Once the head fire had been brought under control, relief crews were brought in and they set about controlling the flank fires. From the time that the head fire had been brought under control until the time that it was finally extinguished, the fire had doubled in size as the flanks moved slowly outwards!

‘However, firefighters who have received wildfire training are most likely to secure a safe anchor point, normally at the tail of the fire, then make their way along the flanks to the head fire. This suggests that they are likely to be extinguishing the most damaging, severe, parts of the fire first. Quite how this would pan out if the fire was heading for a housing estate is yet to be tested.

‘Perhaps a better understanding of the complex nature of these intense head fires will produce new techniques for firefighters. Possibly where Line Fire Equivalent Intensity could make firefighting a little more interesting is during indirect firefighting techniques. Would firefighters ever want to create a very intense counter fire? Or would we want to use the inverse of this to create the lowest intensity fire possible to achieve the objective?

‘At the end of John’s presentation he asks five questions. One of these is, “Can a patterned ignition be used to design a burn?” Clearly the answer to this is yes, and I think that this is most significant for land management. However, my question would be, can patterned ignition be used as a suppression fire, and if so, what would the benefits be?

'John also asks, "Can we, and should we, define severity more tightly?" I think that we should be clear how severity is used in the wildfire context. After talking to firefighters, none of them made the connection between severity and difficulty of suppression. Therefore, I believe that we should take wildfire severity to mean the degree of damage inflicted by the wildfire. I'm not sure where this leaves us with the 'Fire Severity Index' which is actually a prediction of the ease of ignition and the most likely fire intensity.

'This poses a further question; how does Line Fire Equivalent Intensity affect our understanding of the relationship between severity and intensity? Traditionally, high intensity = low severity and low intensity = high severity.

'John has demonstrated that a high intensity, high severity fire can be created via multipoint ignitions, which seem to extend the burning time. Should we, therefore, reconsider how we define intensity? John's equation; equivalent intensity = rate of burning X length of burning region X fraction of area burning, is fine for academics, but do firefighters need a further explanation? Such as 'For complex fires with multiple ignitions in close proximity, high intensity may also equal high severity.'

'Earlier, I said that we should remember that the research fires were intentionally complex to provide evidence in support of the theory. Are UK firefighters ever likely to come across this kind of fire? Well, perhaps we already have. The Swinley fire in 2011 started not from a single point, but from multiple points, fires that had been set in preceding days. They lay dormant, but smouldering, until the conditions were perfect. Combined, they generated extreme fire behaviour with torching and crown fires that were intense, difficult to control and damaging. Does this all sound familiar?'

3.2 George Winn-Darley, Land Manager, The Moorland Association

George was asked to respond to the things he agrees and disagrees with from the presentation. The Moorland Association is concerned with the conservation of heather moorland; George represents the North York Moors and has also been the chairman of the CLA. His background is in land management.

Definitions from other sources: He began with definitions from the Oxford English Dictionary:

> '*Intensity* is the amount of force and also a brightness, violent, strenuous.
>
> *Severity* is rigorous, strict, harsh.'

In the Bushfire Glossary, produced last year in Australia, there are 600 definitions all to do with bushfires, covering 28 pages. Severity is not even mentioned. For Intensity, it refers the reader to Fireline Intensity, and Fireline Intensity repeats John's definition of a release of energy.

Regulations: as far as he can see, the words intensity and severity are not brought up in regulations for land management prescribed burns. Severity is not mentioned at all in the ***Heather and Grass Burning Code***. Intensity gets an indirect mention on p.12;

> '…at least one member of any team should be experienced in predicting flame length, fire intensity and rate of spread and other aspects of fire behaviour and have experience of fire control techniques'.

He felt that there is probably quite a bit of work to be done by all parties to ensure all workers involved in prescribed heather burn do understand fire behaviour and fire intensity better, if land managers are to follow the code properly. He noted that it is mentioned on p.18, where it talks about how wide should a fire break be. The rule of thumb should be two and a half times the flame length. John has explained flame depth, but not flame length. However, flame length is the property cited in the Code that land managers are expected to know about. They are expected to predict the flame length in order to estimate required fire break width.

The ***Wildfire Standard Operating Procedure Handbook*** does not mention it either. He felt that it does expect land managers to be experts on fire behaviour, both current and expected. These are the areas where he felt land managers need to be upping the game a bit, and today has been very helpful.

The ***Met Office FSI*** has a very limited application, being designed to predict the restrictions to public access. At level 5 Access Land is closed to public use. George wondered whether FSI is a misnomer; whether it should be more about intensity rather than severity.

How relevant is the seminar to the land manager's role? George said that: 'If you double the biomass, you quadruple the intensity. If that happens you increase the severity and get severe problems.' As a practical land manager, he felt that it was all to do with the concentration of heat, and that this was the lay man's interpretation of what most of these formulas represent.

He felt that location was very important in estimating likely severity: 'Severity is also to do with where it is and what it is [that is burning].' In a moorland scenario, very suppressed heather might burn, because it is so old and restricted in its growth. If the ground is heavily grazed and reasonably mature vegetation, the likelihood that it will regenerate is almost nil, so the severity of burning is enormous, even though the burn may have been very cool. Similarly, on active blanket bog, which has lots of mosses and has not been burnt previously, the severity of burn is going to be much greater. Archaeological damage can be caused by an inappropriate, intense burn which exposes the archaeology.

The ***DEFRA Best Practice Burning Group*** consists mainly of representatives from the land management and conservation sectors who advise DEFRA on practical guidance documents such as the Heather and Grass Burning Code. It is currently working on a guidance note about wildfire risk. George led on writing the early drafts and drew closely on these in comments on intensity:

'Wildfire is different to prescribed burning. It is not a deliberate act to improve habitat. Wildfires are more intense, release more energy and have a more severe ecological impact, tend to occur in much drier conditions and hotter than prescribed burns; completely removing the litter layer and burning into the peat.

'Fire line intensity is a combination of three factors: heat of combustion, fuel load and rate of spread kW/m. Intense fires are hotter and therefore tend to burn more vegetation. Intense fires spread more quickly, especially where intense fires have a long flame length and where arcing occurs and flames jump a long distance to new fuel loads. Intense fires are therefore much harder to bring under control. Fire intensity increases where there is more biomass in a given area; if you double the biomass you quadruple the fire intensity. It is therefore prudent to make sure habitat does not have too much biomass, with areas of low level biomass which can act as a fire break.'

George thought John's idea of introducing definitions of burn severity and fire severity are very useful and neither of those appear in the glossaries at present, it is something that needs to be worked on.

White smoke; the fact that white smoke shows vegetation is not fully burnt is a helpful point, which people do not fully appreciate. He agreed with the point about some plants burning more energetically, especially gorse.

Flame length: in practical terms, the things he would look at in the field to estimate flame length were dryness of the fuel, wind speed and height of the fuel.

Byram's formula is very good for the scientific community but he could not see how this was going to get used by people on the ground. As Andy said, we need to get this back into simpler bite size pieces. We need to provide the information from this as simple messages for people in the field.

Irregular, unsteady fire lines: George said that separate fronts will occur but do not often interact with each other. They often go off and do their own thing. Occasionally they may come back together and interact.

On slide 12, George would add that burn severity means fire damage not just to vegetation, but also to soil (peat). He didn't agree entirely with John that 'vegetation soil is unlikely to suffer much from a short intense fire'. Intensity which causes dry peat to ignite would be their nightmare scenario; you do not need that much intensity for it to ignite, only an ignition source.

4. Further discussion

Greater Manchester Fire and Rescue Service had recently finished writing National Guidance notes which includes a definition of Fire Intensity as the rate energy is released. Fire Severity was defined in two ways; as size of area disrupted by fire and the amount of damage caused by the fire. This is close to what John discussed.

John found what George had said about guidance for land managers interesting. It was odd that severity was not included.

The ***Met Office FSI*** was discussed at some length:

- We need to change the Met Office FSI rather than make definitions fit it.

- The participant from the Met Office commented that he is relatively new to work on fire, so it is interesting to hear different definitions. Events like this are useful because the Met Office need to understand what stakeholders want.

- In reply, George Winn-Darley said that what he, as a land manager, really wants from the FSI is a series of markers leading up to the point at which Access Land must be closed, rather than a single threshold at level 5. It should be used as part of an awareness-raising campaign. The final tool in the box is closing land.

- John said that the Met office FSI needs developing and renaming, as it relates more closely to fire intensity than severity. The term Fire Danger Index is used by some countries.

- The Met Office replied that the UK FSI was built on the Canadian Fire Weather Index. The UK version uses a power description of fire risk. It is hard to compare with, say, the Australian system. The UK has its own vocabulary.

- Andy Elliott stated it was important to know the likelihood of a fire actually starting. Fire Danger Index would be a better term to use than the Fire Severity Index.

- United Utilities participant said that his water company was a landowner who is interested in controlling fire risk because of its effects on water catchments the resulting need for costly water treatment. In 2011, United Utilities had a very severe fire when the Met Office the FSI was at level 1. It is not what we as landowners are looking for. Also even when the FSI level 5 triggers closure of Access Land (right to roam away from paths), still cannot close the public rights of way (footpaths and roads), so people could still be going through a fire.

- George Winn-Darley commented that press releases about closure of Access Land in his part of the world, the North York Moors, trigger further media interest from regional TV. Although this temporarily raises public awareness, it doesn't help in practical terms because we cannot close public rights of way. What is needed is to manage awareness [earlier].

Fuel

Andy Elliott said that fuel content is the issue, especially in late spring. It's critical in estimating what the severity is going to be, so fuel mapping is needed.

Definitions from the scientific literature

A researcher said that the terms fire intensity and burn severity are well understood in the international scientific literature: [1] It is always important to define precisely what you are referring to; otherwise there is a danger of incorrect interpretation. His suggestions were:

- Fire intensity –a well defined physical term so keep it
- Fire severity – get rid of this term all together!
- Burn severity – meaning impact on the ground, assessed as soon as possible post-fire. Then refine according which part of the ecosystem is being assessed:
    - Vegetation Burn Severity
    - Soil Burn Severity
    - Invertebrate Burn Severity

Question via Twitter: 'Should Fire severity be measured in terms of the number of pumps required to put it out? Who measures it and how?'

The fire service responded that the number of pumps equates to the fire's impact on resource resilience. The Chief Fire Officers' Association recently debated how to define wildfire from the statistics that FRS collect. The number of personnel and vehicles attending a vegetation fire was one of the criteria suggested. The definition affects the number of vegetation fires identified as wildfires, so it is important to get it right. It is the evidence we use to engage the government in wildfire issues.

Assessing burn severity

A researcher said that forest authorities in the USA have to assess burn severity. This is done as part of the Burned Area Emergency Rehabilitation programme (BAER), using Landsat images.[2] In the UK, it could be argued it is the land owner's responsibility to assess burn severity.

Andy Elliott said that in Dorset the land owners record the amount of damage etc. however this can be ad hoc.

[1] e.g. Keeley, J. 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. International Journal of Wildland Fire 18(1) 116-126. doi:10.1071/WF07049 http://www.publish.csiro.au/?paper=WF07049

[2] See for instance, Monitoring Trends in Burn Severity (MTBS) http://www.mtbs.gov/

Peat fires
An environmental consultant expressed interest in what John was doing in South Africa, however it is a very different environment to the peat moorlands she is works in. The peat is riddled with peat pipes, drawing in air and oxygen to help them to burn. Therefore, the model John described could get completely chaotic.

John responded that there are peat fires in Northern Ireland, which are continuously burning and no one has proposed a way of monitoring these. If you do ignite the peat you have a long, low intensity fire.

George responded that peat fires are the most feared enemy for land managers and owners.

John replied that even knowing whether you have a peat fire is very difficult. Smouldering in the peat can go undetected perhaps 2m down below the surface in the peat. Complex ignition patterns can occur.

George felt that thermal imaging cameras could make a big difference and in a wildfire scenario you can look down and can see where to focus the application of the water to put fires out.

5. Post Seminar Thoughts

5.1 Post Seminar Reflection, Andy Elliott: Station Commander, Dorset Fire and Rescue Service

‘As always, listening to the full presentation and the resulting comments during the debate poses new questions and these can only be resolved after further reflection and consideration. Here are my thoughts written a few days after the seminar.

‘The title of this particular talk was “Understanding Fire Intensity and Severity”. It was clear that most people attending had a reasonable grasp of both, as did the people that I had spoken to earlier; but John raised a few issues that made people reappraise their thoughts on both intensity and severity. He also posed five questions:

1. What is a better, more catchy, name for LFE Intensity?
2. Can the measure of intensity for irregular fires be improved further?
3. Can we, and should we, define ‘severity’ more tightly?
4. Can patterned ignition be used to design a burn?
5. Does it have a role in habitat management? – If so, how might it be used?

‘Post seminar, I have given the five questions a little more thought and here are my answers offered as a summary of the debate:

1. 'Byram's formula describes simple fireline intensity, assuming that the fire is regular. John has added a further element to this in an attempt to quantify a more complex type of fireline with irregular shape and interactions with spot fires etc. Perhaps these should be referred to as Simple Fireline Intensity and Complex Fireline Intensity?

2. 'At a scientific level, I'm not qualified to comment, other than to say I hope that the research continues as it is directly relevant to the Fire and Rescue Services around the world in their search for new techniques and appropriate levels of Personal Protective Equipment. However, I think that a consistent method for estimating wildfire intensity in the field is required. It was clear during the discussion that different methods were being used. Some of these were more difficult than others. For instance, some FRS use Flame Height, as an estimate of intensity, while others use Flame Length. Neither method is perfect; flame length is difficult to estimate in the field and there can be confusion between flame length and flame depth. Flame height is easier to estimate, but can become difficult in strong winds when the flame is pushed horizontally. Fire intensity is critical to the safety of firefighters. A reliable, easy to use field estimate of intensity would be a very useful outcome from this research.

3. 'The majority of the debate was about Severity. John proposed two definitions for severity; Burn Severity and Fire Severity. Burn Severity being the term proposed to describe the level of damage to the vegetation, seed bed and soil etc., Fire Severity being the term proposed to describe the difficulty in managing or suppressing the fire. This separation of severity into two clear classes would be helpful. It was also proposed by others present that these terms could be further defined into sub-classes such as Vegetation Burn Severity, Soil Burn Severity etc. as required for clarity. One area of consensus was that the term Fire Severity Index currently in use within the UK was a misnomer as it does not predict fire severity. It was felt that Fire Danger Index would be more appropriate and I fully agree with this proposal.

4. 'I am confident that burns can be designed using patterned ignition, but am not sure how a FRS could make use of this operationally. I am sure that a better understanding of the complex interactions between flaming areas within a wildfire will lead to safer firefighters.

5. 'I am also confident that patterned ignition could have a significant role to play in habitat management. Many of our invasive species are difficult and expensive to control. Areas of lowland heath are being changed because of raised levels of vegetative material within the soils, leading to increased

nutrients. It may be possible to return these areas to low nutrient mineral soils with a high intensity, high severity fire. That not only removes the unwanted vegetation, but also destroys the root systems and returns the soil to its mineral state. If these techniques help to reduce the fuel load within natural landscapes then this would be of benefit to firefighters.'

6. Affiliations of participants

Thirty-nine people registered, 34 attended. Sixty-two per cent were practitioners.

Peak District National Park Fire Operations Group
Moors for the Future Partnership
The Moorland Association
The Heather Trust
The Royal Society for the Protection of Birds, RSPB
Met Office
United Utilities
Dorset Fire and Rescue Service
Lancashire Fire and Rescue Service
Northumberland Fire and Rescue Service
Penny Anderson Associates Ltd
FireLab Ltd
Myerscough College
University of Glasgow
University of Salford
University of Swansea
School of Mathematics, University of Manchester
School of Earth and Atmospheric Sciences, University of Manchester
Manchester Business School, University of Manchester
School of Environment, Education and Development, University of Manchester

Understanding fire intensity and severity

– Implications for managing wildfire and prescribed fire –

John Dold

Emeritus Professor
University of Manchester, UK

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2nd wildfire@manchester event
Knowledge for Wildfire
13th June 2013

MANCHESTER 1824 The University of Manchester

NATURAL ENVIRONMENT RESEARCH COUNCIL

Two terms often used for bushfires or wildfires

Fireline ‘Intensity’

- is the rate of energy release or power (“kW” or “MW”) behind any metre of fire front
- ‘Byram’s formula’ gives its value for a steadily advancing line fire
- but what is the ‘intensity’ for unsteady crooked fire shapes?
- and what does it signify in practice?

Fire/Burn ‘Severity’:

- is a less clear-cut concept
- it has different, possibly conflicting interpretations, such as:

‘Difficulty:’ hard to put out, or leading to large fire scars (as in Met Office FSI)

‘Damage:’ effect of the fire on vegetation or soil

- are these two meanings consistent?

- What links might be expected between **‘intensity’** and **‘severity’**?

Bushfire? What bushfire?

Outline of presentation

- **Basic meaning of ‘fireline intensity’:**

  Intensity of a straight steadily-spreading line fire (looked at from two points of view) combines
  - energy released in combustion
  - degree and efficiency of burning
  - rate or speed of burning

- ‘*Plot-based line fire equivalent*’ **intensity for irregular fires:**

  The challenge (measuring intensity meaningfully)
  and **motivation** (fire control, safety & habitat management)

  A geometrical approach for ‘*line fire equivalent*’ intensity

  Example: a patterned ignition

- **Interpretation** – what does this mean?
- Next steps ...

but first, some comments on Severity

but first, some comments on Severity 4

Burn Severity (as 'fire-effect' on vegetation and/or soil) involves the degree of:

burn-off above ground
root damage and plant-kill
damage to seed-bank
loss of soil (burning of peat or humus, or by soil erosion)

Burn-off may be an objective for habitat management
— other effects we usually wish to avoid

Fire Severity (as 'difficult' to manage, suppress or escape):

Fire Danger Ratings and Fire Severity Indices use weather, soil and vegetation models aiming to predict this

- based on extensive data and analysis in some countries
- data for good 'calibration' is still needed in the UK

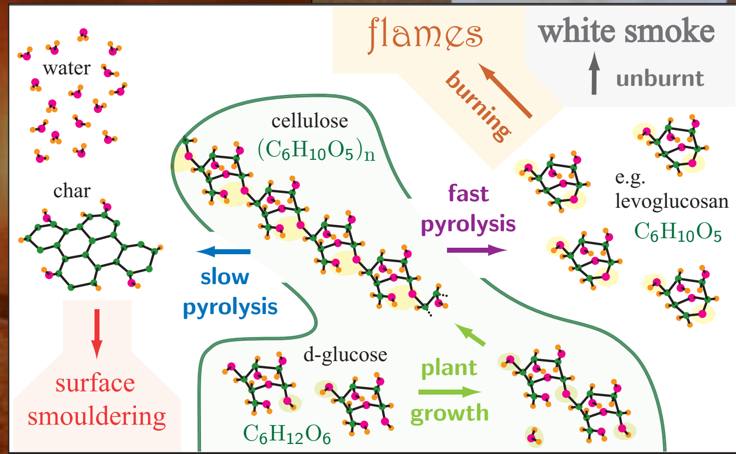
- What are the **links** between **Intensity** and these **Severities**?

  What might be expected?

basics of intensity

burning processes

- example of fast and slow pyrolysis in a sheet of paper (processed wood-pulp)



some plants contain oils and fats that vapourise at lower temperatures than cellulose and burn more energetically

basics of intensity

degree of burning

- example of a sheet of paper (again)

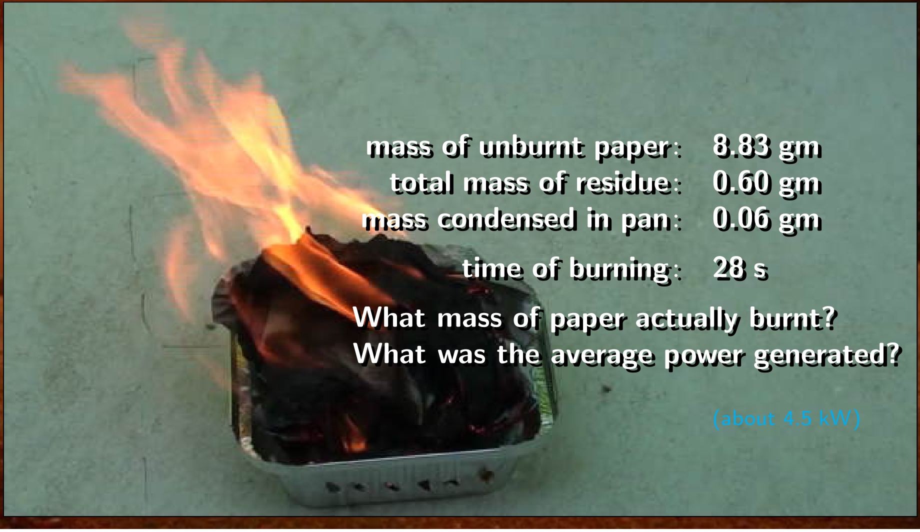
vegetation ⟶
- flammable vapour ⟶ { flames, unburnt vapour }
- unburnt vegetation
- char ⟶ { smouldering, unburnt char }
- ash

- The degree of burning is less than 100% if there is any
  - **unburnt vegetation**
  - **unburnt char** (black residue)
  - **ash** (inert residue)
  - **unburnt vapour** (white smoke)
  - **incompletely burnt vapour** (black smoke)
- Unburnt Vegetation, Ash and Char can be measured
- Harder to quantify unburnt and incompletely burnt vapour

basics of intensity

degree of burning

- example of a sheet of paper (again)



mass of unburnt paper:	8.83 gm
total mass of residue:	0.60 gm
mass condensed in pan:	0.06 gm
time of burning:	28 s

What mass of paper actually burnt?
What was the average power generated?

(about 4.5 kW)

energy of combustion

A typical complete oxidation of cellulose

$$\underbrace{C_6H_{10}O_5}_{162} + \underbrace{6O_2}_{192} \longrightarrow 6CO_2 + 5H_2O \quad \text{(atomic mass units)}$$

Rule of thumb (*using oxygen calorimetry* – [e.g. Drysdale's text])

energy of burning $= 14$ kJ/gm of O_2 consumed

so $Q = 14 \times \frac{192}{162}$ kJ/gm of $C_6H_{10}O_5$ consumed

$Q = 16.6$ kJ/gm of $C_6H_{10}O_5$ consumed

Roughly:

- 60 gm of cellulose burns to produce up to 1 MJ (1000 kJ) of energy

  That is: 12 A4 sheets of paper
  or 8 heaped teaspoons
  of sugar/flour
- 27 gm of carbon produces 1 MJ — *by a similar calculation*
- 52 gm of $C_6H_9O_4$ (typical of wood) produces 1 MJ

Fireline Intensity of a straight steady fire

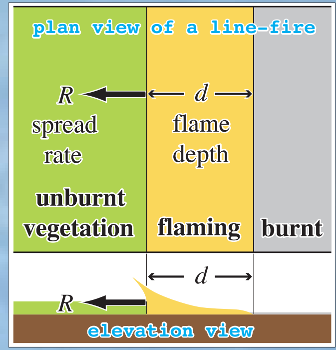
Imagine a fire moving:

at speed (**spread-rate**) R m/s

where the **fuel load** is m kg/m^2

(*reducing m if less than 100% burning*)

burning at an **energy** of Q MJ/kg



Byram's 1st formula gives the intensity as

$$I = QmR$$

so **Intensity increases for:**

faster spread (R), higher load (m) and more complete combustion

Alternatively, if fuel burns during the **flame residence time** (t_b) then **flame depth** (d) is the distance travelled in this time (i.e. $d = Rt_b$)

So $R = d/t_b$ and [*substituting for R*] intensity can be rewritten as

Byram's 2nd formula:

$$I = \frac{Qmd}{t_b}$$

{ [Byram, 1959] uses different symbols }

Intensity of irregular, unsteady firelines

— a plot-based approach

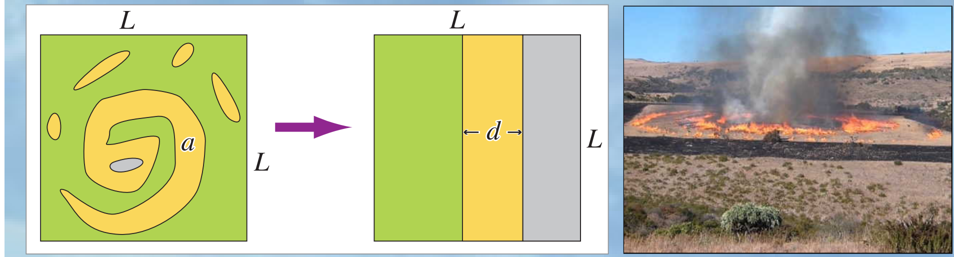
Motivation:

- wildfires are rarely straight
- spotting can create many interacting fires
- patterned ignition can create many different fireline shapes

What is the intensity of such fires?

Intensity of irregular, unsteady firelines

— a plot-based approach



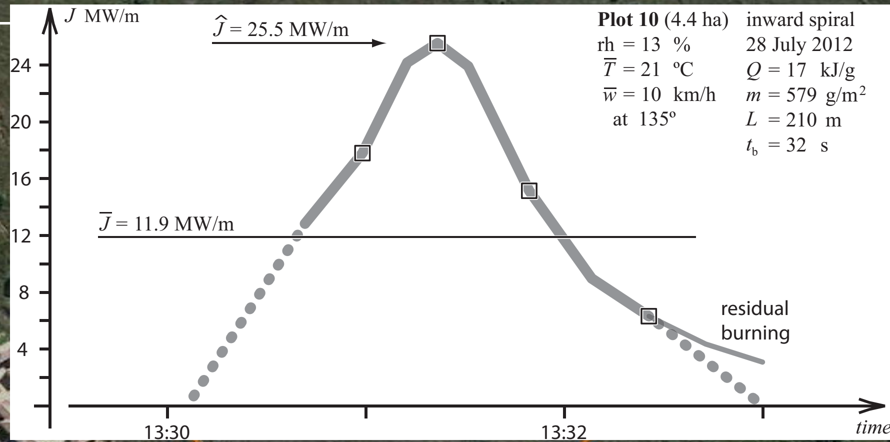
Geometrical approach, for fires in a plot of area $A = L \times L\ \mathrm{m}^2$:

- imagine shifting the total flaming area (a) in the plot into the shape of a straight line fire across the plot
- measure off the resulting flame depth (d) $\{ d = L \times a / A \}$
- then the '**plot-based line-fire equivalent**' (PLFE) **intensity** is

$$J = \frac{Q\,m\,d}{t_b} \quad \text{or} \quad J = \frac{Q\,m\,L}{t_b} \times \frac{a}{A} \quad \left\{ \text{without the geometry} \right\}$$

Intensity increases if the flaming area (a/A) is increased

Intensity of irregular, unsteady firelines

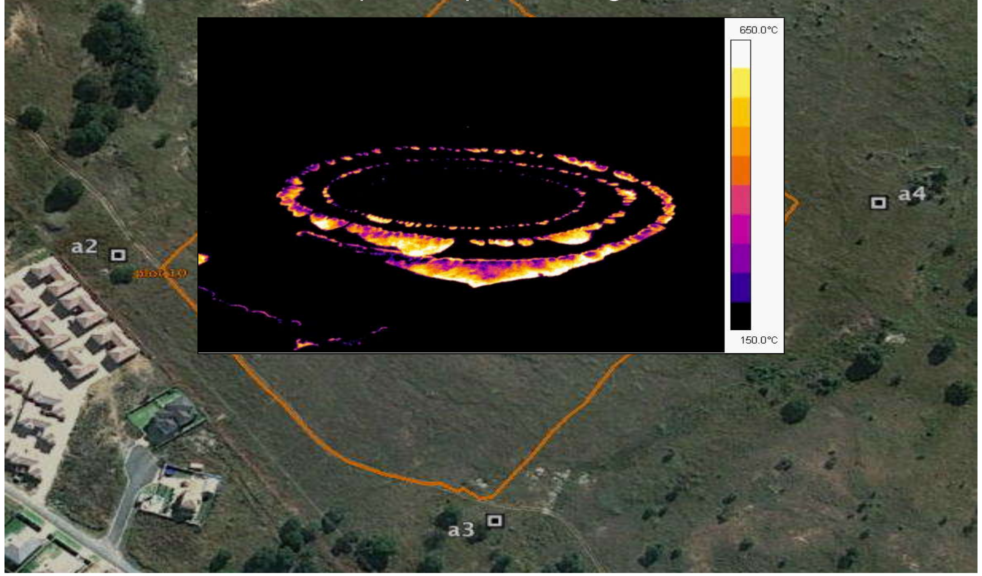


Analysis: taking 'IR temperature' above 300°C to mean 'active flaming' flame residence time (t_b) is found via the analysis

Intensity of irregular, unsteady firelines

— plot-based approach

Example: a patterned ignition



Intensity of irregular, unsteady firelines

— interpretation & next steps

Main implications of increased **PLFE intensity** (J):

- it extends the meaning of **Byram's fireline Intensity** (I)
- equals **Byram's Intensity** ($I = J$) for a steady straight fireline
- measures increased fire activity in an area, where there may be
  - interaction between nearby flaming regions
  - strong convection processes (*fire-whirls observed*)
  - greater flame heights and thicknesses
  - increased flame emissivity (*hence radiation*)
  - enhanced 'burn severity' (... *to be tested*)

Next Steps (*details not given here*)

- developing the formula not to be 'plot-based'
  that is, **LFE Intensity** rather than **PLFE Intensity**
  — or a better name for it? —
- field tests are scheduled for examining effects on vegetation

(Fire or Burn) Severity *and* Intensity

Here it is assumed that

Fire Severity	means	**difficulty in suppression**
Burn Severity	means	**fire damage to vegetation and soil**
Intensity	means	**LFE Intensity**

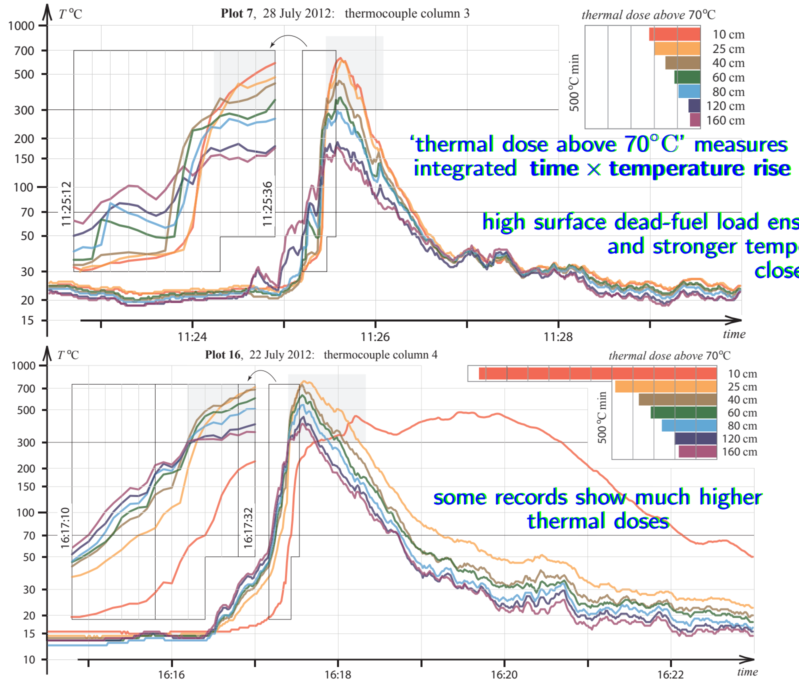
It is likely that **'fire severity'** and **'LFE intensity'** would correlate

For **'burn severity':**

- vegetal damage should relate to heat absorbed, driven by
  - exposure to higher temperature and radiation
  - size, moisture content, conductivity, etc., of the plant
  - the duration of exposure

  higher intensity could increase the first of these
  but a slow fire (lower intensity) *might increase the last*
  - descriptions like '**hot**' and '**cold**' burns miss the point !
- vegetal soil is unlikely to suffer directly from a short intense fire (although this could ignite slow low-intensity smouldering)

Thermocouple Temperature Measurements



summary

Intensity: its calculation for steady line-fires has been extended to irregular fire patterns in plots (**PLFE Intensity**)

There are consistent ways of removing the restriction to plots (. . . *still under development* . . .)

Patterned ignition can greatly enhance intensity.

Severity: Two distinct meanings, **'Difficulty'** and **'Damage'**

Difficulty (**Fire Severity**) and Intensity should correlate

Damage (**Burn Severity**) is very multifaceted

- temperature rise & time **together** cause damage
- 'larger' vegetal components take longer to heat up
- high intensity should damage elevated fuels more

(depending on plant species, condition, structure, etc.)

Ongoing tests will help to clarify Intensity–Severity linkages

major questions

- What is a better, simpler name for **LFE Intensity** ?
- Can **this measure of intensity for irregular fires** be improved further ?
- Can we (and should we) define '**severity**' more tightly ?
- Can **patterned ignition** be used to 'design' a burn?
- Does it have a role in **habitat management** ?
  - if so, how might it be used ?

acknowledgements

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[5] University of Manchester FireLab Ltd