Cooperation or invasion

SUBMISSION TO THE FIRE AND FUELS FORUM
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What is a fuel load?

For over half a century, Australian fire risk management has had the goal of fuel reduction, grounded in the assertion that there is a one to one relationship between 'fuel load' and rate of spread [1,2]. There are two issues with this that undermine management efficacy.

Firstly, no evidence has ever been presented to support the claim that there is a one to one relationship between fuel load and rate of spread; Alan McArthur simply suggested it as a "tentative" observation [3]. Since then it has been directly tested and disproved [4]. That analysis has never been discredited in peer-reviewed literature. My focus here, however, is on the second issue: what is a "fuel load"?

By definition, fuel is simply something that is burnt to produce energy. When leaf litter or grasses burn, they are fuel. When shrubs and tree canopies burn, they are fuel. What then is the fuel load? The weight of leaf litter, or of everything? If we say leaf litter, then we underestimate the fuel that burns in a crown fire. If we include the crowns, then we overestimate the fuel load for a surface fire.

Do the leaves in a shrub have the same effect on a fire as the leaves in leaf litter? Are shrub leaves worth their same weight in litter? The notion of a fuel "load" is that they are the same, because a load is just a weight. In reality though, they are very different indeed.

Consider for example, a litter load of $20t.ha^{-1}$ burning on flat ground, in the afternoon conditions of the 2009 Kilmore fire. Litter moisture is just 4.5% and the wind is $58km.h^{-1}$. Despite these catastrophic conditions, without any plants acting as fuels, the model of Cheney *et al* (2012) predicts a ROS of only $0.03km.h^{-1}$ with 0.2m tall flames. Adding only another $4t.ha^{-1}$ of 1m tall ferns and near-surface fuels as measured by Cruz *et al* (2012) [5], the fire spreads at $15km.h^{-1}$; 500 times faster. If the 3.4m tall midstorey they measured is also included, then flames are predicted to be 192m tall, even though the field guide to Cheney's model [6] says that an extreme elevated fuel hazard only equates to $5\text{-}8t.ha^{-1}$. It is clear that what drives the fire behaviour is not the weight of fuel, but whether that fuel is in litter or plant form.

This is critical to the story. Litter fuels are important because, unless there is enough grass cover, they are the lowest continuous stratum. They carry a small, slow flame - a pilot flame. If only litter fuels are burning, the flame is small enough to control, no matter what their 'load' is. If it then ignites the plants, the flames are much larger. Neil Burrows showed this beautifully in his lab model, which remains the best research to date on the spread of fire in eucalypt litter. When he tried that model in the field where there was up to 54% cover of shrubs, it bore no relationship to the flames he measured there.

Flammability

Here we face another dilemma though. Cruz *et al* only measured the Kilmore fire to have "spread mostly as a high intensity surface fire with isolated torching trees", not a fire with nearly 200m tall flames. How is that possible if there was so much fuel? The authors explain: "This decrease in fire intensity resulted from the lower flammability of this forest type…". The term *flammability* refers to the forest's "ability to burn", either horizontally across the landscape, or vertically through the trees. These equate to general fire behaviour – rates of spread and flame heights [7], so, this statement effectively just says that the fire behaviour was different than expected because it was different than expected. The purpose of a fire behaviour model is to model the flammability of a forest, but it is clear that this model could not capture that flammability. The question is, what did it get wrong?

Consider the fact that the canopy did not ignite, except with isolated torching trees. If it didn't ignite, it wasn't fuel, so it was right not to include it as part of the fuel load. But why only the canopy? What if the 3.4m elevated layer was out of reach of the flames and didn't ignite either? If that happened, it wouldn't have been fuel either, and the modelled flame height would have been only 22m.

But that makes no sense; 22m flames would certainly have ignited a 3.4m tall plant stratum. The only way to avoid that in this modelling scenario is if the near surface plants also failed to ignite and the flame was only 24cm in height from the burning litter. That hardly fits the description of a "high intensity" surface fire though, and it seems improbable under the conditions and that, by definition, the near-surface fuels have no gap between them and the ground. They must have ignited.

How though were 22m flames produced from a 1m tall layer of ferns and other suspended debris? Perhaps this is the issue – the model overpredicted the flammability of the plants themselves. Consider the vast difference in flames predicted from $4t.ha^{-1}$ of these plants compared to $4t.ha^{-1}$ of litter; perhaps not all plants are as flammable. After all, this model was derived from experimental fires in dry West Australian jarrah forest; perhaps rainforest species burn differently?

Perhaps there are other differences as well though – wind speeds beneath old-growth mountain ash trees might be slower than winds under jarrah regrowth. In fact, shorter trees may well have ignited and produced a crown fire, in which case the canopy would also have been fuel, and as it burned away, it would not have protected the fire beneath from the wind at all.

Notice that point: if the canopy ignites, it is fuel and speeds the fire up. If it doesn't ignite, it's not fuel, and it slows the fire down instead.

What would Einstein say?

So, we have a dilemma. It's not too hard to say whether litter will burn or not, that's largely just a question of how dry it is. The problem is that, even though most of the weight of 'fuel' in a forest is in the litter layer, it has almost nothing to do with the severity of a fire or the speed at which it spreads; it's just the pilot flame. If the Kilmore fire had just burnt through $20t.ha^{-1}$ of litter fuels, the Cheney *et al* model suggests it could have been easily contained with a rake hoe. Large flames only occur when plants ignite, but in this case, the flames were nowhere near as large as what was expected by that model. According to Cruz *et al*, they also spread a few hundred metres through the old growth ash in that hour, when the model of Cheney *et al* expects them to spread at $15km.h^{-1}$ – faster than any recorded forest fire so far.

The difference between those scenarios and what actually happened all falls under the heading of flammability. Flammability means that plants make large flames and surface litter doesn't. It means that the flames from some plants are much larger than those from others, that some plants will only catch fire if the plants below them catch fire first and are flammable enough to set them on fire. And – perhaps most confusingly, it means that any plants which don't catch fire actually slow the fire down.

When we talk about fuel load then, we have to first recognise that 'load' has nothing to do with fire behaviour, and that we don't know what is fuel and what is on our side until we unravel this question of flammability. We like fuel load because it's simple. In the well-known paraphrase of Einstein's words though – we should make things as simple as possible, but not simpler. 'Fuel load' has nothing to do with fire behaviour, yet it is the foundation of fire management in Australia. This past fire season has made it clear that it's time we think harder than that.

The story of forests

Surface litter loads recover after fire in a well-understood and distinctive negative exponential curve. There is a fast, initial recovery as litter falls, but the rate of recovery slows as older leaves begin to decay. After a few years, the two processes balance out and litter loads remain roughly level [8]. If there was such a thing as a fuel load, then this would mean that forests reach their maximum flammability a few years after fire, then remain there indefinitely. That would mean one rule to reduce fire risk across all forests: burn them.

As we've seen though, the picture is far more complex. Fire doesn't just remove leaf litter; it burns and scorches plants. At first, that means that there is no continuous medium for fire to spread through, so fire can't spread unless the wind is strong enough to blow it from plant to plant, like a heath fire. The pilot flame is gone. That only lasts a little while though; it only takes a very thin layer of leaves to allow fire to spread, and this can come back in just days as leaves fall from scorched plants. Fire also fertilises the soil and encourages a flush of grass growth, and flames spread quickly and easily through grass. Baring the soil creates a race for dominance: seeds fall from tree canopies into the fresh ash bed, thick coated seeds are heated until the cover cracks open and they germinate, and smoke stimulates germination of numerous other seeds [9]. All of this occurs in an environment where shading vegetation has been reduced or removed entirely, so that can cause two things. The extra light stimulates growth, but the extra heat dries the soil and gives the advantage to drier-climate plants. In some climates there is little difference because they're always dry, but in all environments, the post-fire understorey becomes a nursery for a dense layer of plants growing close to the ground where they can easily ignite. If the last fire was higher in severity, then the plants that used to be above and beyond reach of most flames are now gone. If a fire happens now, the wind at the ground will be stronger than it was before, pushing flames through this dense layer.

Two things happen to the regenerating forest after this. The plants grow, initially creating a denser, taller layer of foliage to ignite and produce larger flames. This is the point that many studies have mistakenly referred to as "long-unburnt", because the forest is green again and the signs of fire are not so easily seen. But although the intervening years may seem long to people, they are short to forests.

As the plants continue to grow, vegetation begins to differentiate itself into strata separated by gaps, and these can become too large for flames to cross. At the same time, dense populations begin to self-thin [10]; their growing environment has limited resources and can't physically support more than a certain weight of biomass. When individual plants are larger, there has to be less of them.

Taller plants now shade lower plants, and there is a shift of biomass so that less foliage grows close to the ground and more of it is sustained higher up, out of reach of many flames [11]. Plants in shade can't grow canopies that are as upright because the lower leaves would be shaded by the upper ones, so they tend to grow shallow and wide [12]. If a plant with a deep, upright crown ignites, the upward-travelling heat finds more foliage to ignite above it, producing a large, deep flame. If a plant with a shallow crown ignites, the flame quickly burns through the top of the crown with nothing else to ignite. Plants growing in the shade also produce thinner, less-dense leaves [13], and these burn out faster [14].

This is the beginning of a mature forest. It may not have developed full wildlife habitat such as hollows yet, but from the perspective of fire, the forest has now become less flammable. Less plants grow close to the ground where they can be fuel, more grow higher in the forest where they slow fire. A mature forest can be a natural landscape control on fire: it has maximum biomass and carbon storage, but this is arranged in the least flammable way. Disturbing it by burning it, digging up the soil or cutting down trees can restart the whole trajectory.

Theory and reality

Some years ago, I collected the mapped fire histories across the SE mountain National Parks in NSW, Victoria and the ACT. Dividing them into different forest groups, I looked at every scar from a wildfire, and at the age of forests it had burnt. The theory was that if forests were more flammable at some age, then on average, each bushfire would be more likely to burn those flammable areas. All I had to do was go through every fire and see how often each age range burnt.

The answer was stark. Every forest from hot, dry open woodland through to tall wet forests and subalpine stands all followed the same pattern: if they had been burnt a few years earlier, they were unlikely to burn again. After this, they were increasingly likely to burn until they peaked some time in the next decade or two, *after which time they became far less likely to burn*. There were three periods of flammability: *young* forests that had just been burnt and were unlikely to burn again, *regrowth* forests that were flammable for decades, and *mature* forests, which were also unlikely to burn [15]. This was not some vague relationship; the curve fit the trend in every forest at the highest level of significance. All this time we had seen these old forests as the most flammable places, but six decades of fire history said we had been exactly wrong. Old forests are the places where fires die.

This fits perfectly with what can be expected from the physical changes in a forest after fire. I've developed a model [16] to calculate the effects of those changes, finding just how flammable different plants are from their leaf traits, and whether fire can spread from one plant to the next. Instead of solving *an* equation, a forest with four plant strata takes roughly half a million calculations to predict behaviour, because fire behaviour is a complex system. What's happening in any given moment depends on what happened in every preceding moment, so every second has to be calculated. As things stand, it's currently the only peer-reviewed model for nearly every forest across Australia, with the exception of West Australian jarrah forests which are also covered by the work of Cheney *et al*.

When I first developed the prototype of the model [17], I used it to examine the how the changes in one community recovering from fire would translate into flammability dynamics, and predicted exactly these three stages [18]. I've since examined Southern Tablelands Dry Sclerophyll forests, taking intensive survey work of areas burnt by prescribed fire and modelling the behaviour we might expect as the forest regenerates [19]. Even low-severity fire in a dry forest that will never develop a wet understorey produces the same trend: a short period of low fire risk after burning, followed by decades of greatly increased risk, then eventually a return to a low-risk forest. The simple fact that plants grow taller and self-thin guarantees it, and it fits exactly with the empirical reality.

Coming of age

The way we understand fuel has stark consequences for the way we manage fire. Years ago, we adopted a simple, but unscientific explanation which tells us that long-unburnt forests are a highly flammable risk. We satisfied ourselves that this was true using case studies, comparing fire behaviour in young forests with that in long-unburnt. Our definition though meant that anything not burnt in the past six years qualified as long-unburnt, so these became comparisons between young and regrowth forest. In three reviews of such case studies, 'long-unburnt' forests were almost never older than the range of regrowth forests I've measured just in the south east [1,20,21], and these are short compared to some. Burning the Great Western Woodlands can initiate a regrowth period that lasts centuries [22].

Leverage studies compare annual wildfire area with the proportion of the landscape that is young or long-unburnt, but we don't look to see whether the 'long-unburnt' category is regrowth or mature forest because our model doesn't make that distinction; all we're interested in is young forest. In the past decade, the NSW National Parks and Wildlife Service burnt more forest for hazard reduction than in any decade before - more than twice the area burnt in the preceding decade [23]. With success: the area of young forest in NSW National parks doubled in the past decade. At the same time though, the faceless category of 'long-unburnt' forest continued to shift from mature forest to regrowth as large blocks of back-country were burnt for cheap hectares. In 1979, 13% of forests in today's National Parks were in a rough regrowth age range of 7 – 30 years. By 2019 that area had nearly tripled to 35%. A flammable community can dominate landscape flammability when it exceeds 20% of the cover [24].

Ecologists have long known that the effect of disturbance is to create dense regrowth; it's called woody thickening [25]. Disturbance gives us flammable forests, but we keep disturbing them because we count the few years of benefit and externalise the decades of cost.

We will not survive if we continue this way.

Learning to live with fire in this country will mean that we stop treating fire science as if it is somehow separate from ecology, that ecology is just about conservation. Ecology tells us we have two options: burn hard and fast to clear plants and prevent regrowth, or let the forests re-establish the mechanisms and arrangements that have long enabled them to survive. There is room in that reality to intensively burn next to assets where such fires have sometimes helped; there is no room to compromise with easy hectares.

Fire in Australia is not about dead leaves on the ground; it is about complex communities of interacting lives. We cannot burn them into submission. We either learn to cooperate, to share the space with these other lives and benefit from their ability to build strongholds against disturbance; or we declare war. We complete our invasion and clear them away.

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