A UNIFIED APPROACH TO FIRE SPREAD MODELLING

A parable of model parsimony

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OUTLINE OF TALK

- Modelling the spread of fire
- Model parsimony
- Review of current models for fire rate of spread
- A simple index for fire spread
- Model comparisons
- Implications and conclusions

MODELLING THE SPREAD OF FIRE

One of the main goals of wildfire research is to provide a relatively simple and timely answer to the question:

“What is the fire’s forward rate of spread”

A number of answers to this question have been provided depending on vegetation type and the availability of empirical fire spread data.

MODELLING THE SPREAD OF FIRE

Fire spread models typically take the form of a mathematical function, or a series of functions, that take environmental data as inputs and deliver an expected rate of spread as an output.

The modelling procedure assumes a parametric functional form for the model, and then appeals to empirical data to estimate the model parameters.

$$R = aU^{b}\exp(-cm)$$

Model parameters a, b and c.

Data

→

Regression analysis

$$R = 6.4211U^{0.9102}\exp(-0.0761m)$$

MODEL PARSIMONY

Occam's Razor or the Law of Parsimony…

A model should be as simple as possible and as complicated as necessary…!

REVIEW OF FIRE SPREAD MODELS

CSIRO GRASSLAND FIRE SPREAD MODEL
(Cheney et al. 1998)

- Rate of spread

$$R = \begin{cases} (0.054 + 0.269U)\,\text{¤}M\,\text{¤}C, & U < 5\,\text{km/h} \\ (1.4 + 0.838(U-5)^{0.844})\,\text{¤}M\,\text{¤}C, & U \geq 5\,\text{km/h} \end{cases}$$

- Fuel moisture factor

$$\text{¤}M = \begin{cases} \exp(-0.108m), & m < 12\% \\ 0.684 - 0.0342m, & m \geq 12\% \quad U < 10\,\text{km/h} \\ 0.547 - 0.0228m, & m \geq 12\% \quad U \geq 10\,\text{km/h} \end{cases}$$

- Fuel availability factor

$$\text{¤}C = \frac{1.036}{1 + 103.99\exp(-0.0996(C-20))}$$

- Fuel moisture content

$$m = 9.58 - 0.205T + 0.138H$$

13+ parameter model...!

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BUTTONGRASS MOORLANDS FIRE SPREAD MODEL
(Marsden-Smedley and Catchpole 1995)

- Rate of spread $$R = 0.678(0.67U)^{1.312}\exp(-0.0243m)(1-\exp(-0.116AGE))$$
- Fuel moisture content $$m = \exp(1.660 + 0.0214H - 0.0292T_{dew})$$
- Dewpoint temperature conversion (Lawrence, 2005 – BAMS)

$$T_{dew} = (T + 273.15)\left[1 - \frac{(T+273.15)\ln\left(\frac{H}{100}\right)}{L/R_w}\right]^{-1} - 273.15$$

$$L = 2.44 \times 10^{6} \quad \text{J/kg at } 25^{\circ}\text{C}$$

$$R_w = 461.5 \quad \text{J/(K kg)}$$

7+ parameter model...!

S.A. HEATH FIRE SPREAD MODEL
(Cruz et al. 2010)

- Rate of spread

$$R = \begin{cases} 0, & P_S < 0.5 \\ 2.455(0.43U)^{1.2}\exp(-0.11m)FHS_{el}^{0.9}, & P_S \geq 0.5 \end{cases}$$

- Fuel moisture content

$$m = 4.79 + 0.173H - 0.1(T - 25) - \Delta 0.027H \qquad \Delta = \begin{cases} 1, & 12:00 - 17:00 \text{ hrs}, \quad \text{Oct-Mar} \\ 0, & \text{otherwise} \end{cases}$$

- Probability of successful fire spread (go/no-go)

$$P_s = \frac{1}{1 + \exp\left[-(2.926 + 2.132(0.43U) - 2.32m + 5.31PCS_{ns})\right]}$$

6+ parameter model...!

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TEMPERATE SHRUBLAND FIRE SPREAD MODEL
(Anderson et al. 2015)

- Rate of spread

$$R = \begin{cases} \left[R_0 + 0.2(3.005 - R_0)U\right] h^{0.22} \exp(-0.076m), & U < 5\,\text{km/h} \\ 5.67(0.67U)^{0.91} h^{0.22} \exp(-0.076m), & U \geq 5\,\text{km/h} \end{cases}$$

- Fuel moisture content

$$m = 4.37 + 0.161H - 0.1(T - 25) - \Delta 0.027H, \qquad \Delta = \begin{cases} 1, & 12:00-17:00\text{ hrs}, \quad \text{Oct-Mar} \\ 0, & \text{otherwise} \end{cases}$$

10+ parameter model...!

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DRY EUCALYPT FOREST FIRE MODEL
(Cheney et al. 2012)

- Rate of spread

$$R = \begin{cases} 30\,\Phi M_f, & U \le 5\,\text{km/h} \\ \left[30 + 1.531\,\Phi F\,(U-5)^{0.858}\right]\Phi M_f, & U > 5\,\text{km/h} \end{cases}$$

- Fuel moisture factor

$$\Phi M_f = 18.35\,m^{-1.495}$$

- Fuel structure factor

$$\Phi F = 1.03\,FHS_s^{0.93}\,(FHS_{ns} h_{ns})^{0.637}$$

- Fuel moisture content

$$m = \begin{cases} 2.76 + 0.0187T - 0.124H, & 12:00-17:00\,\text{hrs, Oct-Mar} \\ 3.60 + 0.0450T - 0.169H, & \text{Other daylight hours} \\ 3.08 + 0.0483T - 0.198H, & \text{Night-time hours} \end{cases}$$

13+ parameter model...!

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SUMMARY OF CURRENT FIRE SPREAD MODEL PARSIMONY

Vegetation type	Number of model parameters*
Grasslands	13
Buttongrass moorland	7
Mallee-Heath	6
Temperate shrubland	10
Dry eucalypt forest	13

* Only considering 'non-fuel' components.

However, from an intuitive point of view, in a particular fuel type/structure a fire should spread faster:

1. ***The stronger the wind***, and
2. ***The drier the fuel***...

This is only 2 degrees of freedom...!?

A SIMPLE INDEX FOR FIRE SPREAD

- Rate of spread should go perhaps something like:

$$S^*(«, p) = \left(\frac{\max(1, U)}{FMI + «} \right)^p$$

2 parameter model.

where, $FMI = 10 - 0.25T + 0.25H$

- Or at worst, after applying a dimensional correction…

$$S(\sim, «, p) = \sim \left(\frac{\max(1, U)}{FMI + «} \right)^p$$

3 parameter model.

A SIMPLE INDEX FOR FIRE SPREAD

$$S(\sim,\text{«},p)=\sim\left(\frac{\max(1,U)}{FMI+\text{«}}\right)^{p}, \qquad FMI=10-0.25T+0.25H$$

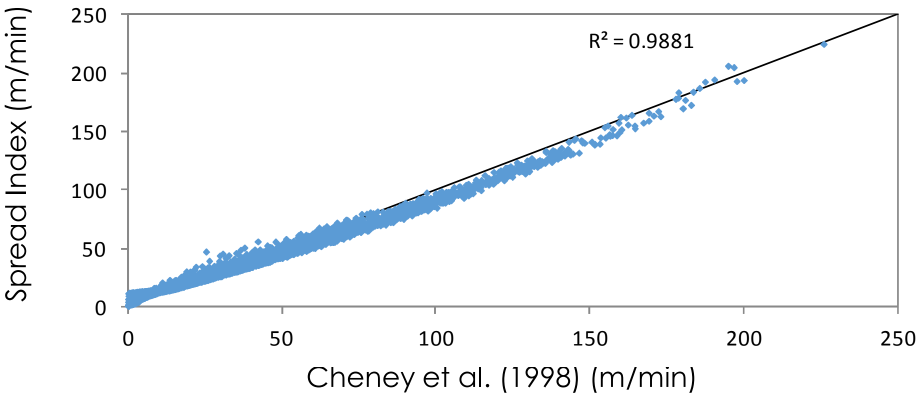
We compare the performance of the simple index with the current operational models for the different fuel types. We assume:

- Fuel factors are constant – so we are only considering the meteorological model components;
- The parameter $\sim$ is defined so that the mean values of the spread index and the predictions of the operational models agree.

MODEL COMPARISON RESULTS

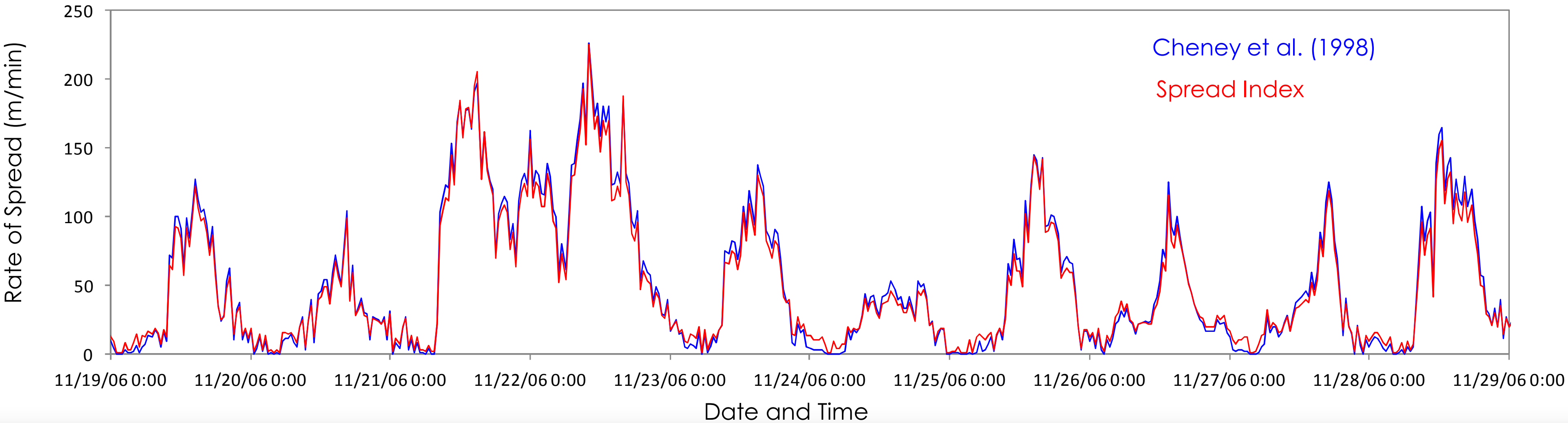
Using approximately 5,000 data points from Canberra airport automatic weather station Nov-Mar, 2006.

GRASSLAND



$$S(\sim, «, p) = \sim \left(\frac{\max(1, U)}{FMI + «} \right)^{p},$$

~ (m/min)	«	*p*
46.1	5.2	1.0



$$C = 100\%$$

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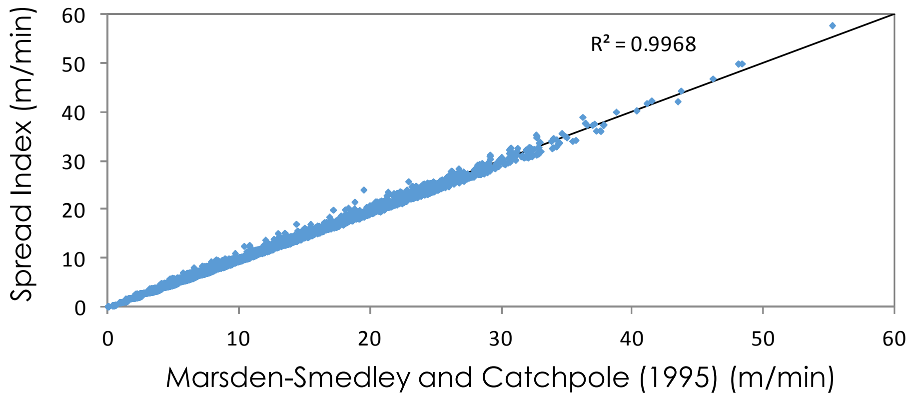
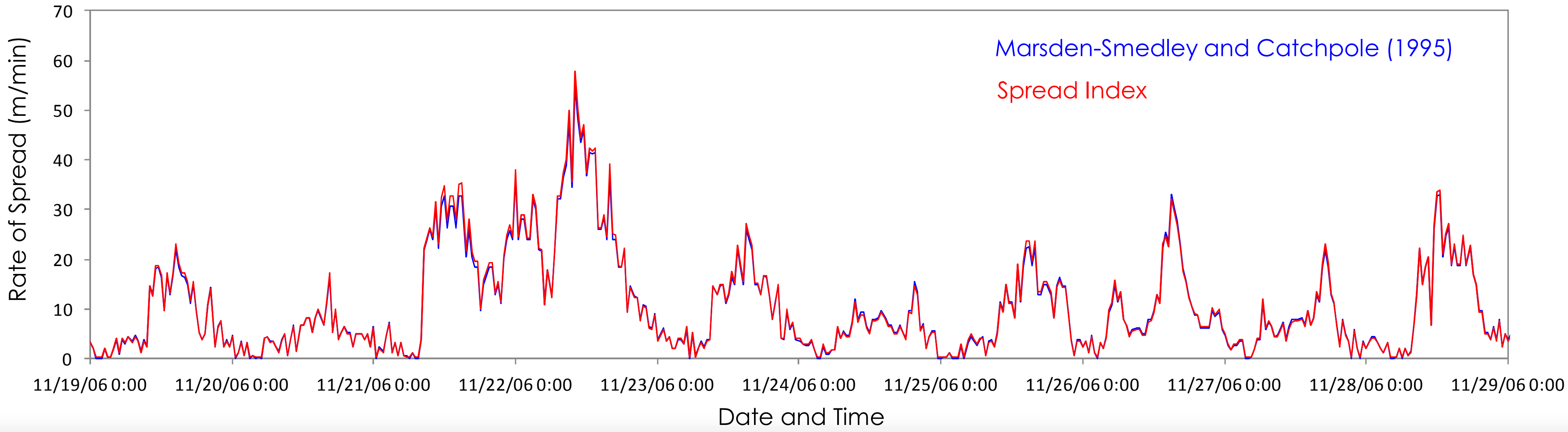
BUTTONGRASS MOORLAND



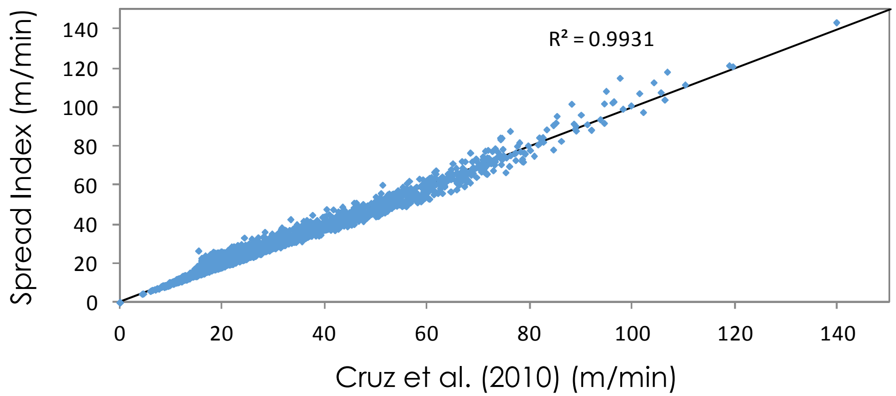
$$S(\sim, «, p) = \sim \left(\frac{\max(1, U)}{FMI + «} \right)^p ,$$

~ (m/min)	«	*p*
104.5	80.0	1.3



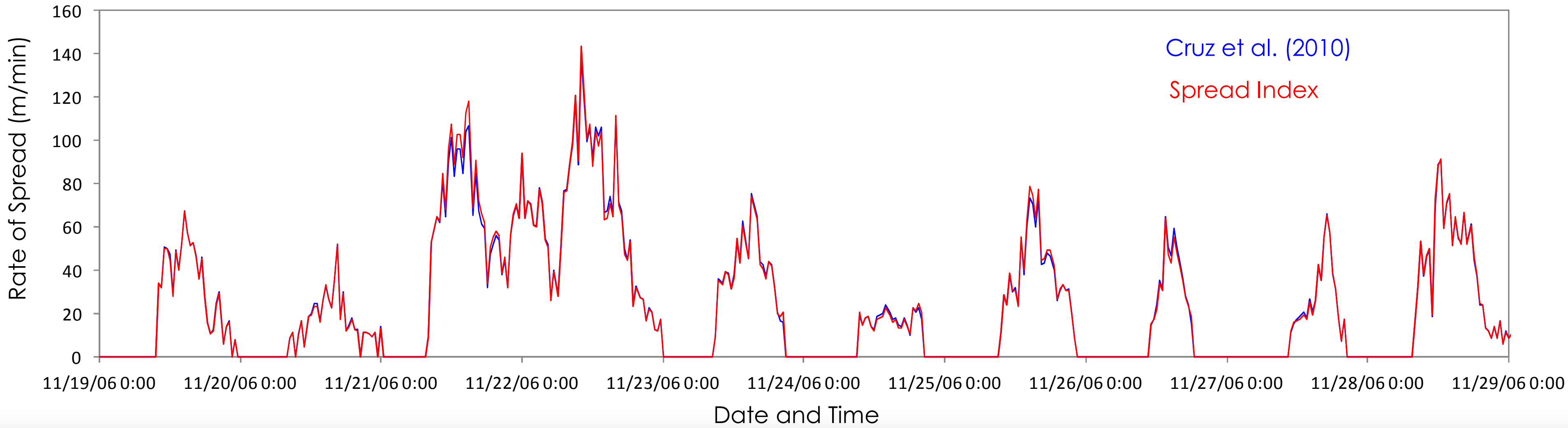
$$AGE = 16 \text{ years}$$

S.A. HEATH



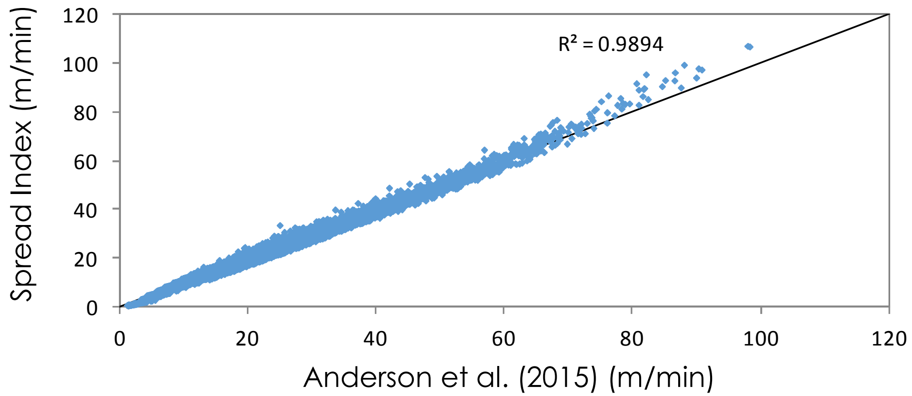
$$S(\sim, «, p) = \sim \left(\frac{\max(1, U)}{FMI + «} \right)^{p},$$

~ (m/min)	«	*p*
27.9	8.0	1.2



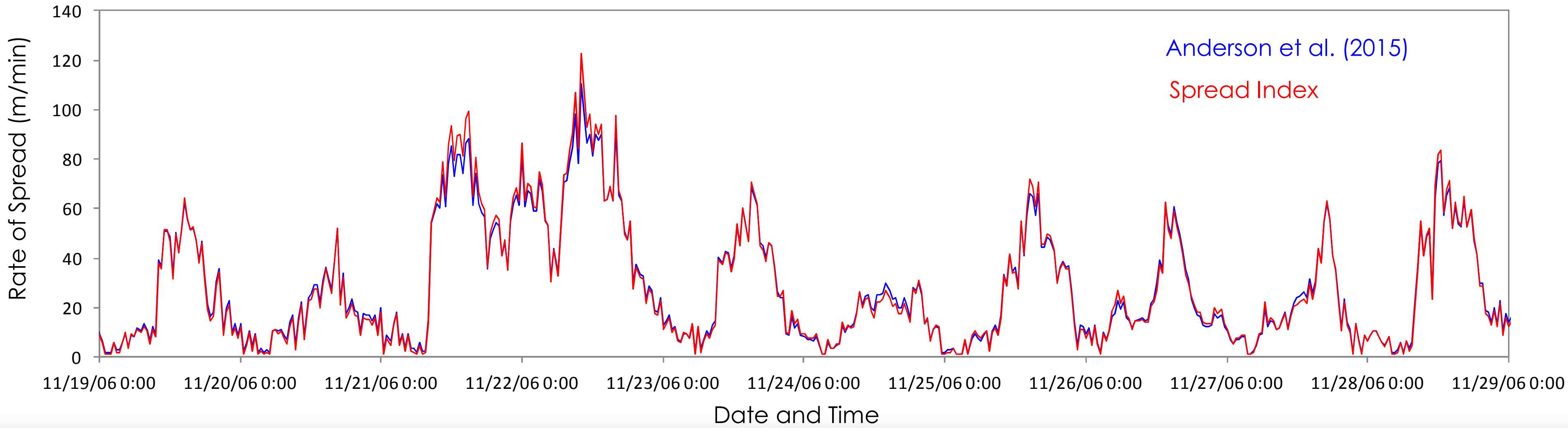
$$FHS_{el} = PCS_{ns} = 3$$

TEMPERATE SHRUBLAND



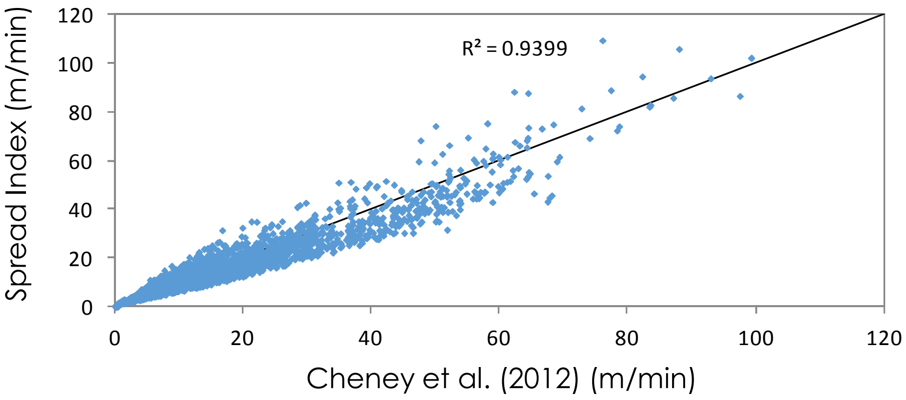
$$S(\sim, \text{«}, p) = \sim \left(\frac{\max(1, U)}{FMI + \text{«}} \right)^{p},$$

~ (m/min)	«	*p*
37.9	11.0	1.0



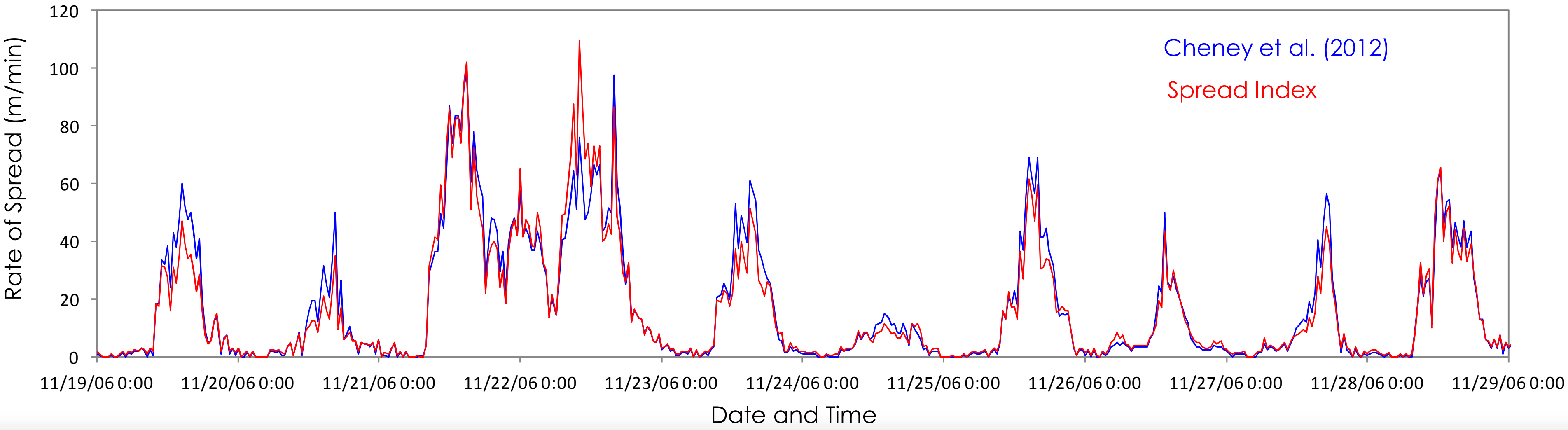
$h = 2$ m

DRY EUCALYPT FOREST



$$S(\sim, «, p) = \sim \left(\frac{\max(1, U)}{FMI + «} \right)^{p},$$

~ (m/min)	«	*p*
10.2	4.0	1.4



$$FHS_s = FHS_{ns} = 2, \quad h_{ns} = 100 \text{ cm}$$

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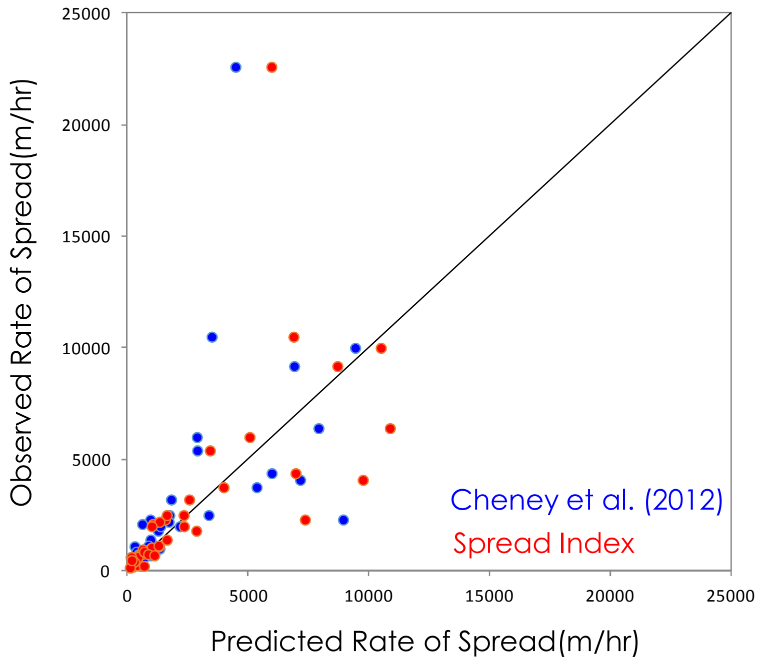
SUMMARY OF MODEL COMPARISON RESULTS…

Vegetation type*	~ (m/min)	«	*p*	R^2
Grasslands	46.1	5.2	1.0	0.988
Buttongrass moorland	104.5	80.0	1.3	0.997
Mallee-Heath	27.9	8.0	1.2	0.993
Temperate shrubland	37.9	11.0	1.0	0.989
Dry eucalypt forest	10.2	4.0	1.4	0.940

* For the particular fuel parameters used.

SOME MORE ON THE DRY EUCALYPT FOREST MODEL…

- Cheney et al. (2012) compare the predictions of the dry eucalypt fire spread model with observations of wildfire rate of spread.
- So we can do the same with the spread index…!

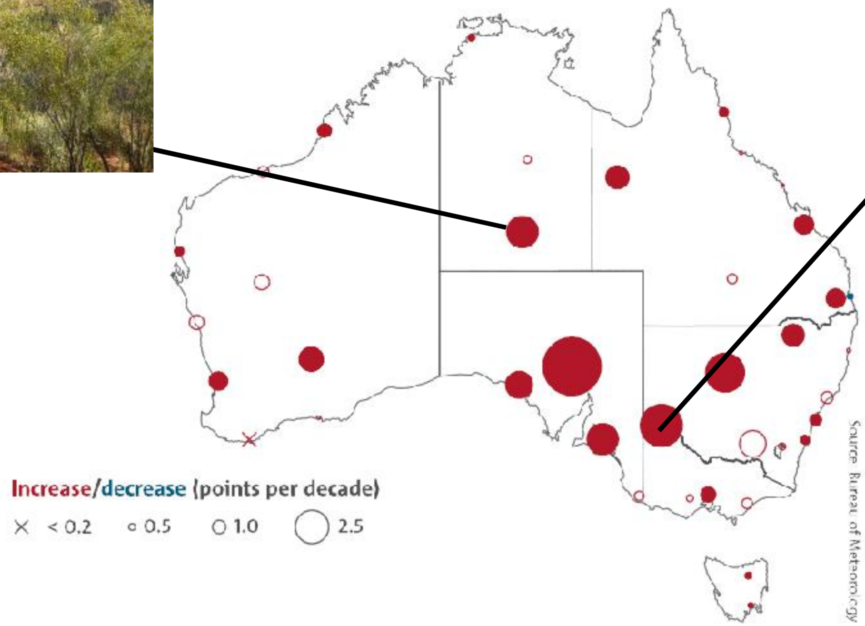


Model	MAE	MBE
Cheney et al. (2012)	51%	-24%
Spread Index*	44%	-8%

* Note that the spread index doesn't incorporate any info on fuel structure, where as the model of Cheney et al. (2012) does!

IMPLICATIONS FOR NATIONAL FIRE DANGER RATING…

Change in FFDI
1974-2015



CONCLUSIONS

- The results confirm, once and for all, that current operational fire spread models are needlessly complicated…!
- A single, *universal* functional form can be used to predict rate of spread across all of the fuel types considered, without any appreciable loss in model performance…!
- The universal model is far more parsimonious, with half to a quarter of the model parameters of accepted fire spread models…!
- The universal model is also far more conceptually simple: rate of spread is essentially 'wind speed divided by fuel moisture content'…!
- Spinifex still presents a bit of a challenge… but fits with the general philosophy...!