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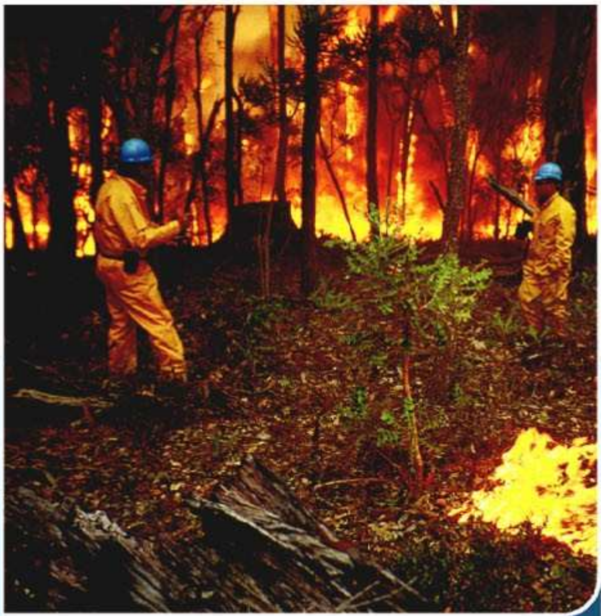

FOREST BIOSECURITY AND PROTECTION

Protecting our forests

Review of methods and data on rural fire suppression resource productivity and effectiveness

Richard Parker, Liz Ashby,
Grant Pearce and David Riley

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Richard Parker, Liz Ashby,
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1. INTRODUCTION

The majority of published reports quantifying the productivity and effectiveness of fire suppression resources are very specific to the fuel type, climate and terrain where the study took place. To date there have been no New Zealand trials of fire suppression productivity and effectiveness of ground resources.

The purpose of this report is to:

a. Provide a review of relevant research on fire suppression resource productivity and effectiveness excluding aerial resources.
b. Provide recommendations for New Zealand research on fire suppression resource productivity and effectiveness.

This report reviews published work on fireline production rates using handcrews, water under pressure and bulldozers. Summary information on fireline production rates are presented and more detailed tables of study results and fireline production rates are included in the Appendices. It should be noted that many overseas productivity studies focus on full-time professional firefighters. This differs from the situation in New Zealand where much fire fighting is undertaken by volunteer and part-time crews.

2. BACKGROUND

Definitions used in this report:

- Fireline – mineral earth or water/foam barrier to fire
- Fireline resource productivity - rate of construction of fireline
- Resource effectiveness - effectiveness of different suppression methods to control fire spread at different levels of fire factors, i.e., fire intensity, flame size, fuel type etc.

For the most efficient use of fire suppression resources, accurate data is needed on fire resource productivity and effectiveness. The data can then be incorporated into fire management decision support systems for pre-suppression planning, initial attack dispatching and the selection of fire suppression strategies and tactics (Hirsch 1996).

Initial attack guidelines incorporate a number of key factors, including fire behaviour, detection and travel times, fuel types, topography, weather and fireline construction rates. Most fire suppression and behaviour studies have been carried out overseas, with limited direct applicability to the New Zealand environment. Fireline production studies have generally considered a few variables such as crew size, training or experience and field classifications such as fuel type (resistance to control and rate of spread categories). The incorporation of fuel types, in particular, within fire behaviour models means that guidelines are specific to the country of origin – however it is possible to match New Zealand fuel types to overseas fuel types in order to apply the guidelines to New Zealand conditions (Fogarty, Slijepcevic & Baxter, unpublished).

Relevant New Zealand fuel types

Forest	Mature pine plantation
	Immature pine plantation – age classes
	Logging slash / cutover
	Indigenous forest - Beech - Podocarp
Scrub	Gorse
	Manuka / kanuka
	Woody hardwoods - Broom / hawthorne - Matagouri
Grass	Pasture - Improved - Unimproved / rank
Tussock	Tall tussock
	Short tussock and tussock pasture
Grass crop	Standing crop
	Stubble

Note: there will be differences between fuel types and fire behaviour with respect to fireline construction and fuel type resistance.

3. PREVIOUS RESEARCH

The fuel type has considerable influence on fire suppression activities. Published research results of fire suppression productivity and effectiveness are difficult to compare because of the great variation in fuel type. In addition, many studies have used simulated fires or expert opinion rather than quantitative field observation to generate data. Other limitations or factors specific to international studies that need to be considered in the New Zealand context are that techniques used elsewhere in fire suppression may be different from those used in New Zealand. Initial attack guidelines and incident management strategies were outlined specifically for New Zealand by Fogarty and Smart (1994), based on Canadian Forest Fire Danger Rating System models and outputs and with consideration of the international literature.

3.1 Hand-crew fireline productivity and effectiveness

Two research approaches have been used to determine the productivity and effectiveness of fireline construction by hand-crews:

- Field trials at real fires, experimental burns or at simulations
- Expert opinion survey.

The summary of previous studies will consider the results of both methods. Table 2 summarises the major findings of the studies.

3.1.1 In-field measurement

Hand-crew fireline construction rates have been reported since the 1930s (McReynolds 1936, cited by Hirsch and Martell 1996). However Haven *et al*. (1982) found that fireline production studies reported production rates that varied by up to

500%. Considerable variation was due to the “resistance-to-control” of various fuel types – based on the average rate of fire spread. Rather than just report the distance of fireline created, Lindquist (1970) reported fireline area from real fires, which took into account the fuel type (e.g., wider fireline in heavier fuels). Lindquist (1970) also created probability distributions of area of fireline created per hour which took into account fatigue. This was the first stochastic representation of wildland fire suppression productivity.

In an attempt to eliminate the need to collect fuel-type-specific productivity data, Murphy and Quintilio (1978) approached the problem of differing fuel types by dividing the hand-crew fireline production task into four components and developing a resistance index for each component. The components were: removing trees, removing brush, removing deadfall or slash and digging a trench to mineral soil. They based the indices on 51 non-fire trials. The index values created were later validated by Murphy *et al.* (1989) in a further series of simulated fire trials with inexperienced crews. Many of the factors associated with real fire suppression such as anxiety, poor visibility and communication difficulties are not present in non-fire trials. Haven *et al*. (1982), Fried and Gilless (1989) and Hirsch and Martell (1996) found substantial variability in production rates due to unmeasured variables.

Barney *et al.* (1992) conducted a study whereby simulated trials, of actual hand-crew fireline construction and training sessions were monitored by observers completing field forms, observing for at least 15 minutes or 50 feet of constructed fireline. The variables included in the study covered considerable ranges, e.g., fireline width from 0.2 feet to 8 feet. A total of 160 observations were made. Useful data were gathered, however the small number of observations for each condition limited the validity, due to the large range of conditions as well as the variables within each condition.

During test burns in Australia, fireline construction rate by hand-crews was found to be inversely-related to head fire intensity (Loane and Gould 1986, cited by Hirsch and Martell 1996). They reported that “fire line construction rate was relatively constant until a critical head fire intensity (e.g., 800 kW/m to 1000 kW/m) was reached and then dropped sharply … for intensities above this point”. If crews believed the head of a fire could be safely suppressed they would work at a fireline construction rate that was constant regardless of fire intensity. But when the fire reached an intensity that was considered beyond their capability they would move to the flanks or stop suppression altogether. Fire suppression with hand tools is generally effective up to a fire intensity of 500 kW/m (Alexander 2000).

3.1.2 Expert opinion

Schmidt and Rinehart (1982) used an expert opinion approach based on ‘several people familiar with each fuel type’, relating fireline productivity to a range of fuel types. They found construction rates ranging from 8 m/person/hour in heavy logging slash to 80 m/person/hour in short grass. However, these rates were not tested against actual wildfires and did not take into account terrain.

To date only one study has considered the simultaneous effects of terrain and slope, elevated fuel (fuel type), presence of active fire and level of firefighter fitness (McCarthy *et al*. 2003a). They collected fireline construction data by interviewing fire staff who attended 103 actual fires in the 1997/98 to 2000/01 fire seasons in Victoria, Australia. They developed a statistical model that explained 57% of the variation in hand-crew fireline construction rate when using slope, elevated fuel and presence of active fire as variables. Active fire was considered to be flames 0.3 m or higher (relative fire intensity of 250-300 kW/m) within 5 m of the hand trail – the lowest threshold at which radiant heat and smoke would inhibit crew activities during fireline construction. The model is described in Equation 1 and the proportion of variation explained by each factor is presented in Table 1.

Equation 1:

$$\text{Construction rate} = 27 + (-10.3*\text{Terrain}) + (-16.2*\text{Elevated fuel}) + (-6.8*\text{Active fire})$$
$$(n=29 \text{ observations}, r^2 = 0.57, p<0.001)$$

Construction rate:	m/person/hour
Terrain:	fireline supervisor's opinion of difficulty of terrain
Elevated fuel:	from "Overall Fuel Hazard Guide" (McCarthy *et al*. 1999)
Active fire:	flame 0.3 m or higher within 5 m of the hand trail

Table 1. Proportion of variation in hand-crew fireline construction rate explained by terrain, elevated fuel and presence of active fire.

Factor	Proportion of variation explained
Adverse terrain, mostly slope	29%
Presence of elevated fuel	19%
Presence of active fire on fireline being constructed	8%
(Fitness of fire crew)[1]	(5%)

McCarthy *et al*. (2003a) found that slope alone did not correlate well with fireline construction rates. The 'Terrain' factor used in the analysis incorporated more than just slope alone: it was the fireline supervisors' opinions of the difficulty of the terrain in terms of slope variations, position in the landscape, ground conditions and slope angle. For example, fireline construction rate on steeper slopes in low foothill country – with little slope variation, less slope length in the landscape and compacted soil with few rocks - was faster than on a less steep slope on a dissected high mountain range with loose soil and rock underfoot.

The model accounts for only 57% of the variation in fireline construction rate. Another 43% is unaccounted for and may be explained through the measurement of other factors (See Section 3.1.3).

McCarthy (2006) reported actual hand trail construction rates in the Wilsons Promontory Fire in South Eastern Victoria of April 2005 agreed closely with predicted rates of 5 m/person/hour.

New Zealand Studies
Fogarty and Smart (1994) reviewed the international literature and produced a table of construction rates developed from Schmidt and Rinehart (1982), Hunt (1986) and Alexander (2000). These are relevant to pine plantation fuel types found in New Zealand.

[1] Fitness was not used in the final statistical model because the effect only became apparent when some outlier data points were removed from the data set.

Specific to New Zealand, Fogarty *et al.* (unpublished) reviewed a number of the overseas and domestic studies to produce information to support initial attack guidelines for use in plantation fuel types.

Main Findings

1. Actual construction rates of 5 to 10 m / person / hour were recorded under real fire conditions.
2. Fireline construction rates under real fire conditions can be considerably slower than those observed under experimental conditions
3. Fireline construction rates are very variable and depend on factors that may not be under the control of the firefighters.
4. Main factors influencing construction rate were terrain, elevated fuel, presence of active fire and fitness.

Table 2. Summary of major findings on hand-crew fireline construction rates.

Study	Year	Factors	Rates	Study type and limitations
Lindquist	1970	Fuel type Width of line	Produced estimates of probability of constructing lines (specifically fireline area) at specified hourly rates. Also compared actual fireline widths with those specified in Fireline notebook[2] 6 m/person/hour (width 1.75 m).	Collected data from 33 actual fires.
Douglas	1973		167 m/person/hour to 233 m/person/hour.	
Murphy and Quintilio	1978	Fuel resistance Smoke & heat Fatigue Flame length	Produced resistance index for fireline construction task elements.	51 Simulated trials. Boreal forest.
Schmidt and Rinehart	1982	Fuel type	8 m/person/hour (heavy logging slash) to 80 m/person/hour (short grass). See Appendix 4.	Expert opinion ('several people familiar with each fuel type'), no field testing. Reflect fuel conditions only. Provides figures for initial attack (unsustained) and for sustained line construction.
Haven, Hunter & Storey	1982	Review	Produced production ranges for specific resistance-to-control classes and study source of estimates (see Appendix 2) 5 - 25 m/person/hour.	Review of previous studies and comparison of data. Substantial variability in production rates due to unmeasured variables.
Quintilio, Van Nest, Murphy, Woodard	1988		Hot spotting 19 m/ person/hour to 403 m/ person/hour. Pulaski and hand pump.	18 simulated fires, two actual fires in boreal forest. Terrain not a factor.

[2] US Forest Service (1963)

(contd)

Fried and Gilless	1989	Fuel type Slope Vegetation density	Grass on flat 240 to 380 m/crew/hour Grass on 25°+ slope 100 to 240 m/crew/hour	Expert opinion survey to obtain estimates of fireline production rates.
Murphy, Quintilio & Woodard	1989	Fatigue	Indicated that the index devised by Murphy and Quintilio (1978) was useful and valid. 27 m/person/hour initial attack 15 m/person/hour sustained[3].	Simulated trials with inexperienced crews to validate resistance indices for task components devised by Murphy and Qunintilio (1978).
Murphy, Woodard, Quintilio & Titus	1991	Flame length Rate of spread	Containment rates between 45 and 403 m/person/hour for variable fire types and characteristics (see Appendix 3).	18 small experimental fires using hot-spotting approach. Large amount of variability in data. Correlation of 0.93 between predicted and measured – see Hirsch & Martell (1996).
Barney, George & Trethwey	1992	Crew size Fuel type Soil type – slower in rocky soil	9 m/crew/hour to 90 m/crew/hour Data difficult to interpret – discrete.	Observation of simulated and actual fires. Several crew and tool configurations. Around 160 observations, with 6 different crew types, variable crew sizes and fuel types resulting in small datasets.
Alexander (Reprinted in 2000)	1992	Fuel type		Review of previous studies and application of data to New Zealand conditions.
Fogarty and Smart	1994	Fire intensity	80m/hour to 160m/hour, depending on initial attack level, for 5 person crew with handtools (see Appendix 1).	Figures based on existing studies (Schmidt & Reinhart, 1982) and adapted to account for effect of fire intensity on rate of fireline construction.
Hirsch and Martell	1996	Numerous	Numerous.	Reviewed previous studies with relevance to Canadian boreal forest fire.
McCarthy, Tolhurst & Wouters	2003	Terrain Elevated fuel Active fire close-by Fitness	2 - 5 m/person/hour to 15 to 20 m/person/hour.	Interview and opinion after actual fires.

3.1.3 Further considerations – Firefighter human factors

McCarthy *et al*. (2003a) reported 43% of the variation in fireline construction rate was unexplained. Firefighter human factors such as levels of physical fitness, work capacity, experience and supervision were not included in their statistical model. The only 'Human Factors' measure quantified by McCarthy *et al.* (2003a) was an estimate of physical fitness. Ordinary crew were rated by fire managers at a fitness level of between 75% and 80%, and rappel crews were rated at 90% to 95% fitness. This

[3] Assuming 45 minutes working and 15 minutes rest or tool maintenance in every 60.

rough measure accounted for another 5% of variation in hand-crew fireline construction rate.

Physiological and other individual human factors can be measured more systematically with appropriate field equipment. Individual variation between firefighters' ability, experience and physical work capacity will influence productivity of fireline construction. Efficiency of fire crews was shown to gradually decrease over time by Budd *et al*. (1991) even under simulated conditions.

The contribution of the following factors to fatigue can be determined by the correct experimental design, appropriate statistical methods and the concurrent measurement of physiological workload:

- Environmental factors - Altitude, heat, humidity, smoke, terrain
- Other factors - Nutrition, fluid intake, shift length, work capacity & aerobic fitness, body composition, training & experience, recovery time
- Command and Control issues (Hirsch *et al*. 2004) – supervision, experience of crew leader.

3.1.4 Recommendations – Hand-crew fireline construction productivity and effectiveness

Measurement of suppression operations should be made under actual fire conditions and analysed using multivariate statistical methods similar to that of McCarthy *et al*. (2003a). Observation at the fireline and personal data logging equipment, such as GPS and heart rate monitors, will enable better estimates of fireline productivity and effectiveness to be obtained. Adequate sample size will be the greatest challenge. Enough observations must be obtained on each major fuel and terrain type. Once preliminary field data is collected and its variability estimated sample size required can be determined.

Where possible, observations of hand-crew fireline effectiveness should also be made together with measurements of fireline construction rates. This could include actual observations of the effectiveness of constructed fireline in holding/containing fire spread from wildfires, prescribed burns, or even experimental fires.

3.2 Water under pressure production rates

Fire suppression production rates for water under pressure have been examined using similar research approaches as hand-crew fireline construction rates: field trials and expert opinion. However, because fewer studies have been undertaken, there is limited data available specific to production rates for water under pressure.

3.2.1 In-field measurement

Douglas (1973) presented water and manpower requirements for fires in south-eastern Australian pine forests. The production rates presented appear to be based on experience and do not refer to measured studies. Wilson (1980) carried out a study in California that collected large amounts of real fire data but with huge variations in conditions. A 2-5 person engine crew produced an average of 732 m/hour of water application in grass and brush fuel types. Increasing the crew size did not result in increases in production rates. There have been few in-field studies of real fire suppression with water under pressure.

3.2.2 Expert opinion

Schmidt and Rinehart (1982) presented tables of productivity (see Appendix 5) developed from input of "people familiar with each type of fuel". The authors warned that the rates presented had not been tested and the rates are for initial action, not sustained action.

Fried and Gilless (1989) used a 'four-estimate' questionnaire approach. For a particular fuel type over a known distance, expert participants were asked to estimate under initial attack conditions:

- "most likely time" to complete fireline of that distance.
- "best case time" - their estimate of time to complete under optimal conditions with fresh experienced personnel, low fire intensity and no hose breaks.
- "worst case time" – estimate assuming imaginable poor conditions of high fire intensity, frequent hose bursts, inexperienced and exhausted firefighters.
- "90^{th} percentile time" – estimate of the time to complete fireline 90 out of 100 times.

They found the limited data that existed from field measurements were optimistic compared with the estimates derived from experienced firefighters.

The Victorian "Park and forest firefighting resources guide" by McCarthy *et al*. (2003b) summarised fireline holding rates for a 4000 litre tanker under Australian conditions. Rates varied from 50 m/hour to 2000 m/hour and were influenced by terrain, wind speed, bark hazard and flame height and behaviour.

More recently Hirsch *et al*. (2004) used an expert-judgement technique in which 141 crew leaders provided estimates of the time to construct 610 m (2000ft) of fireline. This method was used because "…it was the only feasible way to collect the required amount and type of data in a short time at a reasonable cost". A concern with expert-judgement studies is that the opinions expressed may not actually reflect reality. Hirsch *et al*. (2004) stated that the low level of unexplained variation in the statistical models suggests the opinions are credible.

The literature suggests that using water under pressure is effective up to fire intensities of 1500 to 2000 kW/m and flame lengths of up to approximately 1.5 m (Alexander 2000).

Table 3. Summary of major findings on water under pressure production rates.

Main Findings

1. Actual and expert estimation of water under pressure fireline construction rates of 50 m to 2000 m/crew/hour were recorded.
2. Water under pressure fireline production rates are very variable.
3. Critical factors influencing water under pressure fireline holding (productivity & effectiveness) rates were terrain, wind speed, flame height and fuel type.

Study	**Year**	**Factors**	**Rates**	**Study type and limitations**
Douglas	1973		10 to 20 litres water/m of fireline. For success need to apply 10 to 20 litres/m/minute.	SE Australia pine forest – surface fires on pine litter.
Wilson	1980	Fuel type	732m/hour (2-5 person engine crew, laying hose in grass and scrub fuel types) and 1428 m/hour in grass and grass-sage.	Observation of actual fires. Extensive variation in variables.
Schmidt and Rinehart	1982	Fuel type Topography	160 to 800 m/crew/hour for 3 person pumper crew depending on fuel type, i.e., 53 to 267 m/person/hour (see Appendix 5).	Expert opinion ('several people familiar with each fuel type'), no field testing. Reflect fuel conditions only. Provides figures for initial attack and for sustained line construction.
Benoit *et al*.	1989	Fuel type	Produced list of conditions that affected crew capability. Indicated line building rate can vary significantly with fuel conditions.	Simulated conditions, variable crew types. One observation per crew per fuel type.
Fried & Gilless	1989	Fuel type Slope Vegetation density	Crew rates (3 man): Mobile tanker – 200 m/hour to 700 m/hour Hose-lay - 200 m/person/hour to 400 m/person/hour in forest.	Expert opinion Stochastic simulations
Hirsch & Martell	1996			Reviewed previous studies
McCarthy, Tolhurst & Wouters	2003	Wind speed Fuel hazard	4000 l tanker crew rates 100 m/hour – in high winds with spotting and 2 m flames 2000 m/hour – flat terrain, low flame, grass.	Interview and expert opinion after fires
Hirsch, Podur, Janser, McAlpine & Martell	2004	Fuel type Fire intensity Crew size Crew leader experience	54 m/person/hour dead balsam fir. 243 m/person/hour grass.	3 and 4 man crews, 500 & 1500 kW/m intensity, 7 fuel types. Expert judgement interviews.

3.2.3 Further considerations

No studies have taken into account the actual physiological load on the firefighters during fire suppression tasks using water under pressure. Firefighters may have been working at an unsustainable rate when measured. A methodology which measures productivity, load on the firefighter and therefore sustainability of production rate is discussed in Section 4.2.

3.3 Bulldozer fireline production rates

3.3.1 In-field measurement

Douglas (1973) presented the first estimates of bulldozer fireline production rates. These generalised estimates were determined for radiata pine plantations in South Australia. However the estimates appear to be derived from 'rules of thumb'.

Phillips *et al*. (1988) made 196 observations of bulldozer fireline construction over a total of almost 30 kilometres. Using these data and comments by experienced fire managers, they updated previous studies of bulldozer production rates. They reported the major effects on productivity were: slope, bulldozer size, operator skill, condition and age of the machine, amount of rock encountered, vegetation age, vegetation type, vegetation variation, number and size of large trees that need to be removed and air temperature.

Fogarty *et al.* (unpublished) presented a useful translation of US fuel types (used by Phillips *et al.* 1988) to the New Zealand equivalents. The D3 and D85 bulldozer fireline production rates of Phillips *et al*. (1988) were very similar to those reported by Fogarty *et al* (unpublished) from New Zealand wildfires at 250 m/hour and 400 m/hour respectively.

Ponto (1989) provided guidelines for construction of firelines using bulldozers and compared using bulldozers with using manpower. He suggested manpower is used where: the fire is small; larger fires where bulldozers cannot be used, e.g., steep terrain or areas of environmental concern, great distance to fire, or adverse ground conditions. Ponto's (1989) guidelines for the D6H and D6 bulldozers were remarkably similar to actual New Zealand D6H (500 m / hour) and D6 (400 m / hour) bulldozer (and grader) fireline production rates reported by Fogarty *et al. (*unpublished) in the Harakeke (Nelson) and Aupori (Northland) wildfires.

Literature on bulldozer fireline construction rates is summarised in Table 4.

Table 4. Summary of major findings on bulldozer fireline construction rates.

Main Findings
1. Actual bulldozer construction rates of 250 to 500 m / hour were recorded under real fire conditions.
2. Bulldozer fireline construction rates under real fire conditions can be considerably slower than those predicted from expert opinion.
3. Main factors influencing bulldozer fireline construction rate were operator experience, slope, debris, terrain and the presence of rock.

Study	Year	Factors	Rates	Study type and limitations
Douglas	1973	Slash density	800 – 1600 m/h light bulldozer in thinned stand with heavy slash 2000 – 3200 m/h if fitted with V-blade	SE Australia pine forest
Schmidt and Rinehart	1982	Fuel type Slope Bulldozer size	Extensive results for variable slope and bulldozer size, according to different fire behaviour fuel models. Ranges from 100 m per machine hour (small in brush, steep slope) to 2010 m per machine hour (large, flat, open timber/grass under-story) Medium bulldozer (adapted from Schmidt and Reinhart, 1982) • 1509 m/h short grass • 734 m/h tall brush • 694 m/h conifer stand • 785 m/h logging slash	Expert opinion ('several people familiar with each fuel type'), no field testing. Reflect fuel conditions only. Provides figures for initial attack and for sustained line construction.
Phillips, George and Nelson	1988	Slope Operator skill Age / condition of machine Proportion of rock Vegetation type, age Number of large trees to remove Air temperature above 32°C Bulldozer size	Presented a range of rates for small, medium and large bulldozers according to US fuel model Not considered of value to Australian fire managers by McCarthy et al (2003) because of dissimilarities in fuel, terrain and task conditions. However identified bulldozer size, slope class and vegetation type as main factors	Observations during planned prescribed fires
Fried and Gilless	1989	Fuel type Topography Density of stand		Expert opinion on hypothetical fires. Experts required to estimate best, normal and worst fireline construction times. Estimates close to McCarthy *et al* (2003) findings.

Ponto	1989	Height of stand Density of stand Bulldozer HP Cover-type of stand Night or day Slope	500 m/h for D6H 200 m/h for D3 at night	Canadian productivity study combined with expert opinion. Used database of recorded bulldozer hours.
Fogarty, Slijepcevic, Baxter (unpublished)			Table 7 p18. Measured Harakeke Fire, 500 m/h for D6H Ponto (1989) model produced results most comparable to real wildfire observations in NZ	Compared actual productivity data with the other three models
McCarthy, Tolhurst & Wouters	2003	Size of machine Terrain / slope Debris Operator experience Vegetation density		Interview and expert opinion after actual fires

3.3.2 Expert opinion

Bulldozer production rates from expert opinion (Schmidt and Rinehart 1982) were significantly higher than actual production rates recorded by Fogarty *et al*. (unpublished) in New Zealand wildfires.

Fried and Gillies (1989) found that by using an interview method, they could capture the variation in the estimates of productivity. As other workers reported, field study data from simulations were often wildly optimistic. Also the National Fire Danger Rating System didn't reflect all the major conditions that affect productivity, particularly 'local conditions' and vegetation characteristics.

McCarthy *et al*. (2003a) used linear models generated from data collected from expert estimates from real fires to determine bulldozer production rates and the factors influencing bulldozer production rate. The linear model approach has the advantage of pulling together all effects (slope, operator experience) together in one equation.

Equation 2:

$$\text{D4 construction rate} = 595 + (651*\text{DozTerrain}) + (-234*\text{DozDebris}) =+ 1/\exp(-0.9*\text{OperatorTerrain})$$

$$(n=29 \text{ observations}, r^2 = 0.79, p<0.001)$$

D4 construction rate:	m/hour
DozTerrain:	fireline supervisors' opinion of difficulty of terrain
DozDebris:	presence of debris: standing dead and live material, old logs, elevated fuel
OperatorTerrain:	Operator experience in years, in terrain and vegetation similar to the fire site

Table 5. Proportion of variation in D4 bulldozer fireline construction rate explained by terrain, debris and operator experience.

Factor	Proportion of variation explained
Restriction on bulldozer due to the presence of adverse terrain, mostly slope variations, terrain dissection, slope angle and ground conditions	29%
Restriction on bulldozer due to the presence of debris: standing dead and live material, old logs, elevated fuel	19%
Operator experience in years, in terrain and vegetation similar to the fire site	28%

4. Recommendations for the Evaluation of Fire Suppression Productivity

4.1 Introduction

This review has identified that there is limited information available that is directly applicable to the New Zealand conditions. Local research is therefore required.

4.2 Human response to work

Measurement of heart rate is required as a minimum to determine the physiological response to work. Heart rate provides an unambiguous measure of how hard the body is working. With this information a particular fire suppression task can be quantified in terms of the effort required to complete the task. Performance of the firefighter over time, can also be measured with heart rate. Very physically demanding tasks such as carrying a pump uphill, can only be sustained for a short period of time because heart rate and energy expenditure are very high. Energy expenditure can be calculated as the area under a heart rate by time graph and determined for common fire fighting tasks. Fried and Gilless (1989) caution that field trial production rates are unlikely to be normally distributed but skewed toward faster rates. Given that most field studies suffer from a lack of replication, knowledge of the variation in productivity due to the human response to work is essential. This is new information that has not been collected before.

4.3 Physiological work capacity and fatigue

The individual's capacity for work can be estimated by measuring heart rate against increasing power output on a cycle, treadmill or stepping ergometer. In this way heart rate can be used to measure how close to fatigue and/or exhaustion firefighters are working when performing suppression tasks. The results of such analyses can be used to predict how long a particular work rate can be maintained. This is vital when rating tasks for effort required achieving them. For example there is the risk that firefighters race each other to complete suppression tasks when measured at a simulated fire. The resultant estimates of firefighter productivity would be higher than those reported from real fires when firefighters were fatigued. Heart rate measurement will identify when firefighters are working faster than at a sustainable rate. To date no studies have combined heart rate with suppression of real fires. Trying to determine the productivity of a firefighter without measurement of the physiological response to work, (i.e., heart rate), can be likened to selecting an engine without knowing its rated power output.

4.4 Measurement of manual hand-crew and water under pressure fire suppression productivity

Productivity should be measured on firefighters constructing fireline using hand tools and water under pressure under normal operational conditions, i.e., real fires, experimental fires or burn-offs. The use of modern, lightweight and relatively unobtrusive data-logging equipment and video technology should allow the firefighters to work unencumbered while productivity data is collected. It is envisaged that firefighters being studied would wear heart rate monitors and personal data-logging GPS units. Their activities would be observed and recorded with body-mounted video cameras. In this way the start and end of individual fire suppression tasks such as laying out hose, applying water or mopping-up can be recorded and matched with heart rate during those tasks. The distance each firefighter moves during the task will be measured by their GPS unit. Additional information and timing of events will be collected by examination of video recordings and real-time data collection using field computers.

4.5 Bulldozer fire suppression productivity

With the availability of GPS recording equipment, bulldozer productivity rates should be relatively easily calculated from actual fire activities. Many modern bulldozers have computer data logging of key engine parameters that may be used to determine detailed datasets of bulldozer activity for further analysis. Also, improved supervision and recording of heavy machinery usage at wildfires will yield better data for analysis.

5. CONCLUSIONS

Productivity of initial attack crews, and more specifically, of fireline construction has been of interest for many years and has been the subject of numerous studies. Surprisingly few studies have actually measured productivity under real fire conditions. Little material, other than McCarthy (2006) has been produced in terms of new data, since the commonly cited studies of Schmidt and Rinehart (1982), and Barney *et al.* (1992), and most of the studies have produced either limited or extremely variable data, restricting the validity and applicability of the resulting guidelines. Most of the current guidelines are adapted from these early studies, although their validity is enhanced through application of local conditions and of expert knowledge and information.

However, the need for information specific to New Zealand conditions remains, and this combined with the availability of new technology, in particular for monitoring the effects/importance of human factors, means that significant advances/improvements can (and should) be made to existing data and guidelines through research on productivity (and effectiveness) of fire suppression resource types mobilised in New Zealand.

The suggested priority areas for further human factors based work are as follows:

1. Water under pressure
2. Hand-crews without water
3. Bulldozers

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7. APPENDICES

Appendix 1.

Fireline construction rates for forests, logging slash and grass for different techniques at each of five different initial attack levels (from Fogarty and Smart 1994).

Table A1 - Fireline construction rates (m/hour) for forests

Initial attack levels	1 (0-10 kW/m)	2 (10-500 kW/m)	3 (500-2000 kW/m)	4 (2000-4000 kW/m)	5 (> 4000 kW/m)
Fireline construction technique	Fireline construction rate (m/hr)				
5 person crew with hand tools	160	160	130	100	80
3 person smoke chaser	80	80	60	50	40
5 person pumper crew	400	400	320	260	200
Hot spotting crew	600	600	480	390	300
Bulldozer	600	600	480	390	300

Table A2 - Fireline construction rates (m/hour) for logging slash

Initial attack levels	1 (0-10 kW/m)	2 (10-500 kW/m)	3 (500-2000 kW/m)	4 (2000-4000 kW/m)	5 (> 4000 kW/m)
Fireline construction technique	Fireline construction rate (m/hr)				
5 person crew with hand tools	100	80	80	65	50
3 person smoke chaser	60	80	50	40	30
5 person pumper crew	400	400	320	260	200
Hot spotting crew	750	750	600	490	380
Bulldozer	750	750	600	490	380

Table A3 - Fireline construction rates (m/hour) for grass

Initial attack levels	1 (0-10 kW/m)	2 (10-500 kW/m)	3 (500-2000 kW/m)	4 (2000-4000 kW/m)	5 (> 4000 kW/m)
Fireline construction technique	Fireline construction rate (m/hr)				
5 person crew with hand tools	400	400	320	260	200
3 person smoke chaser	240	240	200	150	120
5 person pumper crew	800	800	650	520	400
Hot spotting crew	1200	1200	950	800	600
Bulldozer	1500	1500	1200	980	750

Appendix 2.

Rates of construction of fireline for U.S. Forest Service Pacific Southwest and Pacific Northwest Regions, by fuel type and source of estimates (chains per hour per person) (adapted from Haven et al. 1982, with added conversion of chains to metres [1 chain = 20 m].

Fuel type	Fireline handbook		Snowcroft et al (1966)	Stevenson (1951)	Buck (1938)	US Dep. Agri. Forest Service (1938)	Lindquist (1970)	
	Basic rate	After 8 h					1 h	8 h
1	4.0 [80]	2.1 [42]				2.9 [58]	1.2 [24]	0.6
2	3.6 [72]	1.8 [36]	1.0 [20]			1.8 [36]		
3	4.7 [94]	2.5 [50]				2.4 [48]	0.8 [16]	
4	3.7 [74]	2.1 [42]				2.2 [44]		
5	2.7 [54]	1.4 [28]				1.5 [30]	0.8 [16]	0.5
6	1.4 [28]	0.7 [14]	0.5 [10]		1.1 [22]	1.5 [30]	0.8 [16]	0.5
7	2.7 [54]	1.4 [28]	0.8 [16]			1.4 [28]	0.8 [16]	0.5
8	1.4 [28]	0.7 [14]	0.7 [14]			1.1 [22]	0.8 [16]	0.5
9	1.2 [24]	0.6 [12]				1.0 [20]	0.8 [16]	0.5
10	1.1 [22]	0.6 [12]			1.1 [22]	1.0 [20]	0.8 [16]	
11	0.7 [14]	0.4 [8]	0.7 [14]	0.3 [6]		0.6 [12]		
12	0.7 [14]	0.4 [8]		0.5 [10]		0.5 [10]		
13	0.4 [8]	0.2 [4]	0.3 [6]	0.22 [4.4]			0.5	0.2
14	0.3 [6]	0.2 [4]				0.7 [14]	0.3	0.2
15	0.5 [10]	0.3 [6]						
16	1.2 [24]	0.6 [12]						
17	6.2 [124]	3.1 [62]						
18	0.7 [14]	0.4 [8]						

Fuel descriptions – the authors', based on descriptions given in the publications:

1. Grass
2. Grass and scattered sage
3. Mature timber – little chopping
4. Bear cover
5. Open manzanita – patchy brush
6. Timber – medium reproduction and brush
7. Light-to-medium chamise
8. Brush mixtures with sage
9. Medium brush – in cutover or timber burn
10. Mixed Douglas – fir-white fir, with brush and reproduction
11. Medium brush and oak
12. Heavy pure manzanita, chamise or buckbrush
13. Heavy mixed brush
14. Heaviest mixed brush
15. Second growth – medium poles
16. Slash in cutovers
17. Woodland – little chopping
18. Mature timber

Appendix 3.

Dominant tree species, fire behaviour, crew characteristics and hot-spotting containment rates for 18 test fires in northern Alberta (from Murphy et al.1991).

Fire no.	Dominant tree species	Fire behaviour			Ave. rate of spread (m/min)	Max. rate of spread (m/min)	Flame length (m)	Relative fire size (m/man)[a]	Crew type	Hot-spotting containment rate (m/man-hour)
		Running	Candling	Crowning						
86-01	Jack pine	Yes	No	No	2.80	4.0	0.33	20.0	Man-up	242
86-02	Jack pine	Yes	Yes	No	1.30	5.0	0.44	18.8	Helitack	342
86-03	Jack pine	Yes	No	No	0.60	5.0	0.33	26.8	Man-up	403
86-04	Jack pine	Yes	No	No	1.00	1.5	0.33	42.7	Helitack	230
86-05	Black spruce	Yes	Yes	No	1.50	2.0	0.75	16.5	Helitack	156
86-06	Black spruce	Yes	Yes	Yes	3.30	6.0	1.00	13.3	Helitack	164
86-07	Black spruce	Yes	Yes	Yes	2.10	5.0	2.00	13.2	Helitack	364
86-08	Black spruce	Yes	Yes	No	2.10	5.0	1.50	10.7	Man-up	246
87-20	Jack pine	Yes	Yes	No	1.00	2.0	0.25	23.3	Helitack	192
88-30	Jack pine	Yes	No	No	1.20	1.7	0.50	27.2	Helitack	328
88-31	Jack pine	Yes	No	No	2.70	4.0	1.25	16.4	Man-up	175
88-32	Jack pine	Yes	No	No	2.70	4.0	1.40	27.0	Man-up	235
88-33	Black spruce	Yes	Yes	Yes	7.50	12.0	7.50	43.1	Man-up	45
88-34	Black spruce	Yes	Yes	No	1.40	3.0	4.00	14.9	Helitack	123
88-35	Black spruce	Yes	Yes	No	5.00	10.0	8.50	21.7	Man-up	70
88-35A	Black spruce	Yes	Yes	No	5.00	7.0	2.50	13.7	Man-up	94
88-36	Black spruce	Yes	Yes	No	2.00	4.0	3.50	26.6	Helitack	133
88-37	Black spruce	Yes	Yes	No	1.40	3.5	1.75	17.7	Helitack	401

[a] Relative fire size is the length of fire perimeter per crew at the time of initial attack

Appendix 4.

Line production rates for initial attack action by hand-crews (from Schmidt and Rinehart 1982) with added figures converted to metres/person hour in parentheses.

Fire behaviour fuel model		Conditions used in	Construction rate	
			Chains/person hour	**(m/person hour)**
1	Short grass	Grass Tundra	4.0 1.0	(80) (20)
2	Open timber/grass understory	All	3.0	(60)
3	Tall grass	All	0.7	(14)
4	Chaparral	Chaparral High pocosin	0.4 0.7	(8) (14)
5	Brush (2ft)	All	0.7	(14)
6	Dormant brush/ hardwood slash	Alaska black spruce All others	0.7 1.0	(14) (20)
7	Southern rough	All	0.7	(14)
8	Closed litter timber	Conifers Hardwoods	2.0 10.0	(40) (200)
9	Hardwood litter	Conifers Hardwoods	2.0 8.0	(40) (160)
10	Timber (litter and understory)	All	1.0	(20)
11	Light logging slash	All	1.0	(20)
12	Medium logging slash	All	1.0	(20)
13	Heavy logging slash	All	0.4	(8)

Appendix 5.

Line production rates for initial attack action by pumper crews (from Schmidt and Rinehart 1982) with added figures converted to metres/crew hour in parentheses.

Fire behaviour fuel model		Conditions used in	Rates in chains per crew-hour (m/crew-hour in parentheses)				
			Number of persons in crew				
			1	*2*	*3*	*4*	*5+*
1	Short grass	Grass	6 (120)	12 (240)	24 (480)	35 (700)	40 (800)
		Tundra	2 (40)	8 (160)	15 (300)	24 (480)	30 (600)
2	Open timber/grass understory	All	3 (60)	7 (140)	15 (300)	21 (420)	25 (500)
3	Tall grass	All	2 (40)	5 (100)	10 (200)	14 (280)	16 (320)
4	Chaparral	Chaparral	2 (40)	3 (60)	8 (160)	15 (300)	20 (400)
		High pocosin	2 (40)	4 (80)	10 (200)	15 (300)	18 (360)
5	Brush (2ft)	All	3 (60)	6 (120)	12 (240)	16 (320)	20 (400)
6	Dormant brush/	Black spruce	3 (60)	6 (120)	10 (200)	16 (320)	20 (400)
	hardwood slash	All others	3 (60)	6 (120)	12 (240)	16 (320)	20 (400)
7	Southern rough	All	2 (40)	5 (100)	12 (240)	16 (320)	20 (400)
8	Closed litter timber	Conifers	3 (60)	8 (160)	15 (300)	20 (400)	24 (480)
		Hardwoods	10 (200)	30 (600)	40 (800)	50 (1000)	60 (1200)
9	Hardwood litter	Conifers	3 (60)	7 (140)	12 (240)	18 (360)	22 (440)
		Hardwoods	8 (160)	25 (500)	40 (800)	50 (1000)	60 (1200)
10	Timber (litter and understory)	All	3 (60)	6 (120)	12 (240)	16 (320)	20 (400)
11	Light logging slash	All	3 (60)	8 (160)	12 (240)	16 (320)	20 (400)
12	Medium logging slash	All	3 (60)	5 (100)	10 (200)	16 (320)	20 (400)
13	Heavy logging slash	All	2 (40)	4 (80)	8 (160)	15 (300)	20 (400)