CSIRO PUBLISHING
International Journal of WILDLAND FIRE

RESEARCH PAPER
https://doi.org/10.1071/WF25311

International Association of Wildland Fire

Empirical models of initial attack fire behaviour reduction by skimmer airtankers in Ontario's boreal forest

Melanie Wheatley[A,*] and Mike Wotton[B,C]

For full list of author affiliations and declarations see end of paper

***Correspondence to:**
Melanie Wheatley
Ontario Ministry of Natural Resources, Aviation Forest Fire Emergency Services, Sault Ste. Marie, ON P6A 6V5, Canada
Email: melanie.wheatley@ontario.ca

Received: 9 January 2026
Accepted: 11 September 2026
Published: 15 October 2026

Cite this: Wheatley M and Wotton M (2026) Empirical models of initial attack fire behaviour reduction by skimmer airtankers in Ontario's boreal forest. *International Journal of Wildland Fire* **35**, WF25311. doi:10.1071/WF25311

© 2026 The Author(s) (or their employer(s)). Published by CSIRO Publishing on behalf of IAWF.
This is an open access article distributed under the Creative Commons Attribution-NonCommercial 4.0 International License (CC BY-NC)

OPEN ACCESS

ABSTRACT

Background. Airtankers are used during wildfire initial attack suppression to reduce fire behaviour and enable ground suppression, yet there is little empirical evidence on how suppression from airtankers reduces fire behaviour. **Aims.** To quantify the relationship between airtanker suppression effort (i.e. number of water drops) and fire behaviour reduction for two commonly used skimmer airtankers (Canadair CL-415 and DHC-6 Twin Otter) in Ontario's boreal forest. **Methods.** Probabilistic models were developed to estimate the likelihood that airtanker suppression reduces fire behaviour to a smouldering state as a function of suppression effort using 17 years of operational observations recorded by air attack officers. **Key results.** The probability of fire behaviour reduction increased with greater suppression effort. CL-415 airtankers required fewer drops than Twin Otters to achieve similar reductions, with differences most pronounced at more severe fire behaviour levels. Suppression from CL-415 airtankers showed that aerial suppression can be effective when active crowning is observed. **Conclusions.** Aerial suppression meaningfully reduces fire behaviour across a range of conditions but often requires greater suppression effort than predicted by theoretical models. **Implications.** Results provide empirically derived suppression effectiveness models that can support airtanker deployment decisions, dispatch optimisation and suppression system simulation under current and future fire regimes.

Keywords: aerial suppression, boreal forest, fire rank, fireline intensity, initial attack, Ontario, ordinal logistic regression, statistical analysis, waterbomber, wildfire, skimmer airtanker.

Introduction

Wildfire management agencies engage in aggressive fire response operations to try to keep unwanted fires small (Brown and Davis 1973), with very few fires escaping containment efforts. These few fires that escape initial attack account for the majority of fire suppression costs (Calkin *et al.* 2005) and area burned across the landscape (Stocks *et al.* 2002; Hanes *et al.* 2019, 2025). The initial attack (IA) response to fires in Canada often involves aerial suppression support from either fixed or rotary-wing aircraft owing to their ability to arrive at a fire and start suppression efforts quickly and drop large amounts of water or suppressant. However, few studies have quantified the effectiveness of aerial suppression including the impact of water or suppressant applied by airtankers on fire behaviour (Plucinski 2019*a*, 2019*b*, Plucinski 2025) and very few of these studies involved the analysis of observations of fire suppression operations in the Canadian boreal forest (Hirsch and Martell 1996; Wheatley *et al.* 2025).

Airtankers are used for both IA and extended attack (or support missions) (McFayden *et al.* 2023) to aid ground crews in fire suppression. The type of airtanker used, whether it be a land-based airtanker, a skimmer airtanker, or a rotary-wing airtanker varies depending on geographical location. However, generally on IA, airtankers will action small fires to reduce fire intensity and limit fire growth to allow ground suppression crews to action the active edges of the fire. On large extended-attack fires, airtankers will often work on sections of the fireline where ground crews are not working to cool

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

hotspots, hold sections of fireline and reduce the intensity of small spot fires to smouldering combustion. In the province of Ontario, Canada, skimmer airtankers, or 'waterbombers', are used owing to the abundance of water bodies throughout the province. Ontario maintains a fleet of nine CL-415 airtankers (water capacity of approximately 6000 L of water per drop) and three DHC-6 Twin Otter airtankers (water capacity of approximately 2000 L of water per drop). Only water or water with foam enhancers is currently dropped from airtankers in Ontario.

In Ontario, an air attack officer (AAO) accompanies the airtankers in a separate aircraft (known as a 'birddog' aircraft) to provide strategic direction and support for the airtankers. The AAO is responsible for determining the tactical plan for suppression, directing both drop placement and the number of drops required. They must do this while considering the observed fire behaviour, values at risk, the availability of nearby water bodies for the airtankers to pick up water from and the anticipated IA ground crew arrival time. Suppression tactics can vary depending on fire behaviour and mission objectives, but it is common for airtankers to build holding lines using strategies such as 'tagging on' or 'rolling up', where drops are slightly overlapped as the airtankers progress around the flaming edge of a fire. Drops can also be layered (i.e. stacked) on top of one another to increase the amount of water hitting the active combustion zone and the forest floor, and therefore the suppression line's ability to hold the fire perimeter. These line-building strategies are often carried out using a circuit of airtankers, with two or more airtankers often dispatched and dropping one after another on the same fire (McFayden *et al.* 2023).

Most fixed-wing airtanker suppression is executed on IA; for example, in Ontario, 67% of fixed-wing aerial suppression missions are on IA.[1] Aggressive suppression action during this phase is critical to prevent small fires from escaping containment and growing large. Our understanding of the impact of airtanker suppression on fire behaviour is limited and based primarily on landscape-scale statistical modelling of IA suppression effectiveness, commonly referred to as IA success (Korkola *et al.* 2024). These studies have examined the relationship between airtanker use and IA success with respect to fire size, the type of fuel in which the fire was burning, fire behaviour and other factors (e.g. McCarthy 2003; Plucinski 2012; Collins *et al.* 2018; Wheatley *et al.* 2022; Rezaei *et al.* 2023). Research has found that the amount of suppression effort applied by airtankers on IA was the strongest predictor of IA success; however, as suppression effort increases, the associated probability of IA success decreases (Calkin *et al.* 2014; Wheatley *et al.* 2022). This counterintuitive association seems to represent a paradoxical result where more suppression effort leads to a lower probability of IA success, a finding attributed to the tendency to apply greater suppression effort on more demanding fires, which may nonetheless achieve other operational objectives such as protecting values at risk or limiting fire spread to certain areas (Wheatley *et al.* 2022). Others have similarly found that fires actioned by air attack have a higher IA escape potential (Stonesifer *et al.* 2016; Katuwal *et al.* 2018), likely because airtankers are usually dispatched to fires that exhibit more extreme fire behaviour on the assumption that air attack is required to contain them. However, an important distinction is that these studies did not explicitly examine the airtanker suppression effects on fire behaviour, but rather, only the overall result of the suppression effort on a desired outcome within the fire suppression system.

When studying the impact of water on fire behaviour, this impact is often measured in terms of the extent to which it reduces fireline intensity, the rate of energy release per unit time per unit length of fire front, expressed in units of kilowatts per metre, often described using visual characteristics such as flame length, height and depth (Byram 1959). Fireline intensity is an important metric to measure with respect to airtanker effectiveness because thresholds based on estimated fireline intensity are generally believed to indicate when ground crews are no longer effective or safe at suppressing a fire (and therefore when airtankers are required for suppression) and when direct attack from airtanker suppression will no longer be effective (commonly stated as a head fire intensity of over 4000 kW/m, or when crown fire activity is observed) (Hirsch and Martell 1996; Taylor and Alexander 2018). These thresholds, however, are based on observations of limits of control in Australia (e.g. Hodgson and Heislers 1973; Luke and McArthur 1978), and although used across the boreal forest, their applicability has not been directly examined.

Some studies have examined the impact of water on fire behaviour using physical modelling. Such studies predict the theoretical amount of water required to extinguish a fire (e.g. Loane and Gould 1986; Hansen 2012; Penney *et al.* 2019; Van Wagner and Taylor 2022) and specify the water depth required to cool combustion zones at specified fireline intensities. Moreover, an airtanker drop effectiveness assessment framework has been developed, using a physically based energetics model, for a suite of rotary and fixed-wing airtankers commonly used throughout the boreal forest (McFayden *et al.* 2023); this model specifically examined the impacts of the water contained in a drop on both the energy within a combustion zone and the

[1]This statistic is obtained from analysing the data used in the current study. An aerial suppression mission is considered as IA if the mission is conducted on the same day that the fire was first actioned.

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

unburned fuels beside the drop. This represents a drop tactic commonly used in direct suppression operations, where airtanker drops are targeted so that half of the drop's width is on the flame front and half is on unburned fuels.

Little has been explicitly quantified in terms of the direct impact of airtanker drops on fire behaviour on free-burning wildland fires in the Canadian boreal forest. The development of statistical models to explore this impact of suppression on fire behaviour can be challenging owing to data limitations and the difficulty in measuring and documenting fire behaviour metrics, such as fireline intensity during fire suppression operations. Instead, fire behaviour characteristics such as spread rate and fire rank are often reported from the fireline. Fire rank is a commonly used indicator of fire behaviour in Canada similar to fireline intensity class; however, fire rank is more of a qualitative characterisation of fire intensity made from the observation of flame length and fire type (i.e. surface, torching, crowning) (British Columbia Wildfire Service 2025).

The need to study airtanker effectiveness on IA and quantify the ability of suppression action to reduce fire behaviour is motivated by several factors. Airtankers are limited, expensive resources and cannot be deployed to every IA fire and they are not always effective on vigorously spreading (i.e. high-intensity) fires (Keating *et al.* 2012). Fire managers must decide which fires are most likely to be contained by airtankers and how much suppression effort will be required to achieve such effectiveness. These decisions require a robust understanding of the limits of airtanker effectiveness, an understanding that will become even more important as climate change makes wildfire decision-making increasingly challenging. In this study, we develop empirical models of airtanker suppression effectiveness using nearly two decades of operational observations recorded by AAOs in Ontario's boreal forest. We model the probability of reducing fire behaviour to a smouldering state as a function of suppression effort, quantified by the number of airtanker drops applied around the fire perimeter, and explicitly compare the performance of two commonly used skimmer airtankers: the Canadair CL-415 and the DHC-6 Twin Otter.

Methods

Data

Observed fire behaviour and suppression data

Detailed data on airtanker missions were obtained from the Ontario Ministry of Natural Resources (OMNR). This database consists of all fixed-wing air attack missions in Ontario from 2007 to 2023. A mission was defined as the period from the arrival of the AAO and airtankers at a fire until their departure (e.g. move to another fire, head to a base for refueling, achieved mission objectives). This dataset includes detailed information about each mission including: the time of arrival and departure of the airtankers from the fire, the estimated fire size at time of arrival and departure and primary fuel type at the fireline, as well as observed fire behaviour and response attributes such as the fire's estimated rank and spread rate (estimated by trained and experienced individuals), and the number of drops on the fire during the mission.

To isolate the effect of airtanker type on fire behaviour, we created two datasets: one for the CL-415 airtanker (~6000 L per drop) and one for the DHC-6 Twin Otter airtanker (~2000 L per drop). Missions involving mixed airtanker types or different aircraft borrowed from a province or territory were excluded. This analysis focused on IA suppression (as opposed to extended attack missions) where airtankers were assumed to be working the entire fire perimeter or most of the fire perimeter; therefore, fires that were greater than 25 ha in size when air attack arrived were removed.[2] Only air attack missions that occurred between 1 May and 30 September were included owing to inconsistency in daily fire weather reporting outside this period.

Weather data

Daily fire weather observations from 2007 to 2023 were obtained from the OMNR fire weather station archive. Canadian Fire Weather Index (FWI) System (Van Wagner 1987) outputs calculated at 1300 Local Daylight Time (LDT), but representative of the day's peak burning conditions, were interpolated to each fire location on the date of air attack using a thin plate spline method in the 'fields' package in R (Nychka *et al.* 2017). The Fine Fuel Moisture Code (FFMC), which represents the amount of moisture in the surface litter fuels, the Build-Up Index (BUI), which represents the amount of fuel available for combustion, and 1300 LDT observed wind speed were used to estimate surface fuel consumption for fire behaviour calculations (Fig. 1) using the Canadian Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992).

Model framework

The impact of airtanker suppression on fire behaviour, as characterised by the qualitative observation of fire rank provided by the AAO at the start and at the end of the mission, was modelled using ordinal logistic regression. The estimated fire rank when air attack arrived at the fire before suppression is referred to as $RANK_{PRE}$, and the estimated fire rank when air attack departed the fire is referred to as $RANK_{POST}$. A proportional odds logistic regression framework was used to predict the probability of $RANK_{POST}$ of a given fire, where $RANK_{POST}$ is an ordinal outcome with discrete categories, each of which represent a level of K. Here,

[2]We recognise that there is not one specific size or time to containment definition for the initial attack phase of fire (e.g. Korkola *et al.* 2024).

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

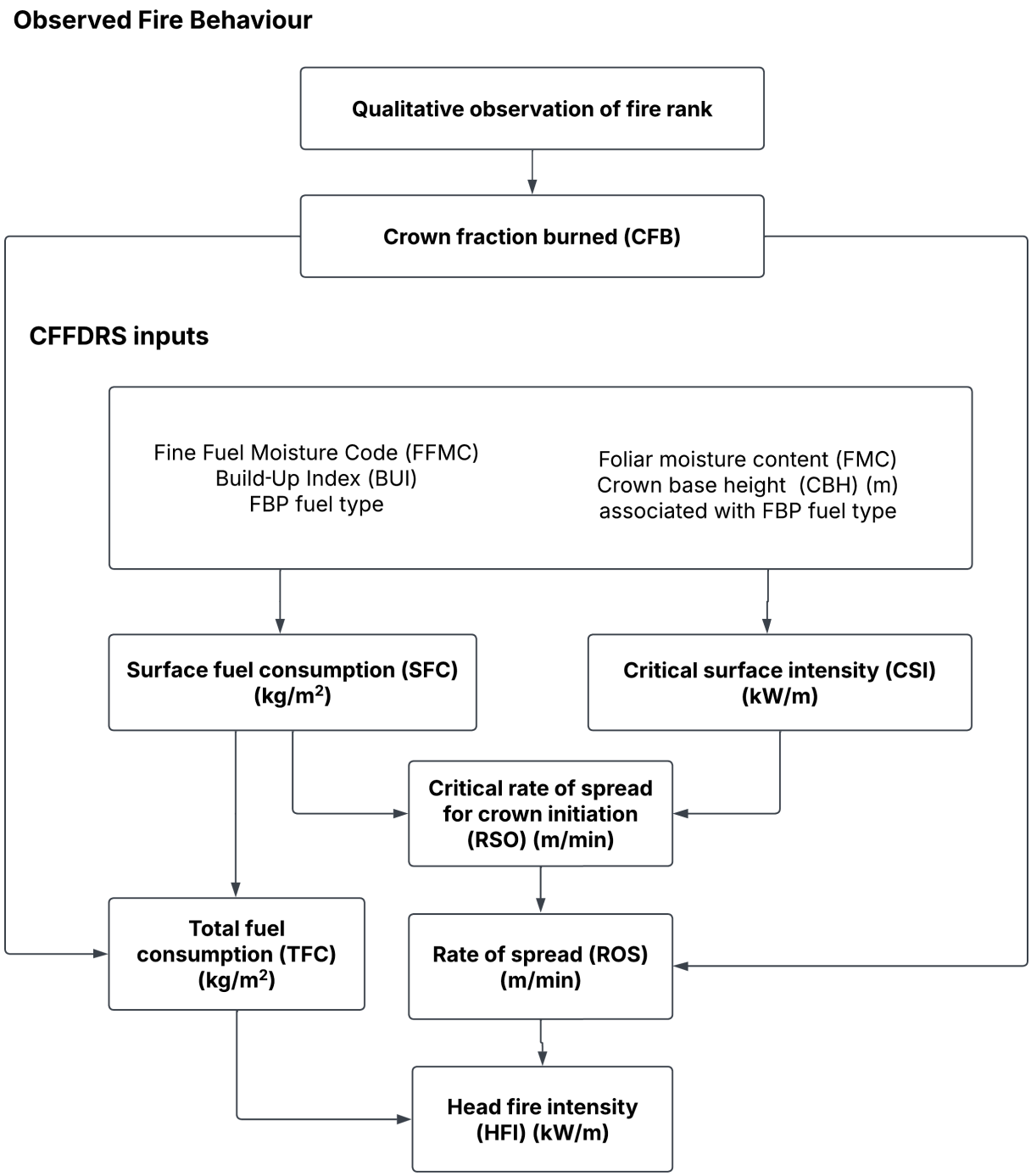

Fig. 1. Flowchart of the calculation of Byram's head fire intensity for each fire using the qualitative observation of fire rank observed at the start of the air attack mission and attributes from the Canadian Forest Fire Danger Rating System (CFFDRS). The calculation of head fire intensity uses observed fire rank to estimate the crown fraction burned (CFB), or proportion of crowning. Head fire intensity is then estimated given the Fire Behaviour Prediction (FBP) System fuel type identified on the fire. Refer to Supplementary material Appendix A for a worked example of the head fire intensity estimation.

the probability of an equal or smaller response, $Y \leq K$ is compared with the probability of a larger response, $Y > K$ (Hosmer *et al.* 2013). Therefore, the probability of $Y > K$ can be modelled as:

$$P(Y > K) = \frac{e^{-(\boldsymbol{\beta_{K0}} - \beta_1 X_1 - \ldots - \beta_q X_q)}}{1 + e^{-(\boldsymbol{\beta_{K0}} - \beta_1 X_1 - \ldots - \beta_q X_q)}}$$

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

where K represents one of the $RANK_{POST}$ categories, $\boldsymbol{\beta_{K0}}$ is a vector of the intercepts for each category K and β_j is the regression coefficient that represents the slope for a given predictor variable $X_j, j = 1, \ldots, q$, where q represents the number of predictor variables.

The proportional odds logistic regression model assumes that the impact of a unit change in X on the odds of Y being in a higher ordinal category is β_n, regardless of K; therefore, there is only one regression coefficient associated with each variable in the model, which represents the slope of the variable for all levels of K. However, each level of K has its own intercept, $\boldsymbol{\beta_{K0}}$, to reflect the changes in the four different categories. Two proportional odds logistic regression models were developed to capture and quantify the impact of airtanker suppression on fire behaviour, one for the Twin Otter and one for the CL-415 airtanker.

Model inputs

When considering the factors that influence the ability of airtanker suppression action to successfully alter the state of fire behaviour, it is helpful to consider what is occurring operationally during a typical IA mission. When airtankers arrive at a fire, the AAO assesses the fire's current behaviour, characterised by fire rank, and directs the aircraft to drop directly on the active fireline with the objective of quenching flames, cooling the combustion zone and reducing fire behaviour to a state where ground crews can safely engage the fire (as described in the Introduction). Each drop delivers water across a portion of the fire perimeter, and airtankers typically work in circuits, progressively building a suppression line around the perimeter with successive passes. Therefore, important factors to consider for modelling are: the initial fire behaviour prior to suppression, which can be represented by the qualitative indicator of fire behaviour and growth potential *STACK*, the length of fireline that the airtankers are working and the amount of actual suppression (or number of drops) that the airtankers are applying onto the fireline. When arriving at a fire with an uncontained perimeter longer than the airtanker's effective drop length, building a containment line around that entire perimeter will require multiple drops, even if only a single drop were required to hold any single part of that perimeter. The number of drops applied on the fireline will likely then scale in multiples of the number of drops required to 'ring' the perimeter once. Therefore, this model uses the number of drops needed to circle the perimeter once to scale the total observed number of drops, producing a metric we refer to as *STACK*, which estimates the degree of drop layering over the fire perimeter. *STACK* is calculated by dividing the perimeter length of the fire by the estimated effective drop length of a CL-415 or Twin Otter airtanker given the fire intensity around the perimeter. To calculate the elements that influence *STACK*, a series of assumptions must be made about the fire perimeter length, fireline intensity, effective drop length and amount of suppression applied. The sections below describe these calculations and assumptions used.

Estimating fireline perimeter length

The observed fire behaviour and suppression database described earlier provides two estimates of the size of the fire, one when the AAOs arrived at the fire prior to suppression, and one when the AAOs departed at the end of the mission after suppression activity. Both fire size estimates were used to estimate the length of the fire in the head fire spread direction at the start and end of suppression; this assumed the fire was spreading as an ellipse with a length-to-breadth ratio of 2.0, using the elliptical approximation for perimeter from the FBP System (Forestry Canada Fire Danger Group 1992). To estimate the length of perimeter being worked on over the duration of the mission, the average of the perimeter on arrival and perimeter when the AAOs departed the fire was taken. This average perimeter length, P_{AVG}, was used rather than relying solely on the perimeter on arrival (or departure) to account for the growth of the perimeter that would have occurred over the duration of the mission, because more drops will have to be applied to hold a longer perimeter (Fig. 2).

Estimating fireline intensity

Determining the amount of suppression (i.e. the number of drops) required to 'ring' the fire perimeter depends on fireline intensity, as higher-intensity fires release more energy and require greater water volumes to reduce combustion to a flameless state. McFayden *et al.* (2023) provide a method that, for a range of airtankers used in Canada, estimates an effective drop length that depends on the fire intensity and fuel type a fire is burning in. The FBP System provides estimates of potential rate of spread and head fire intensity each day based on FWI System outputs. These estimates, however, represent peak burning conditions (~1700 LDT) and may not reflect the actual conditions during suppression. Although spread rate can be estimated visually by personnel on site, fireline intensity is not directly observable. Field observers typically infer intensity from flame length using an empirical intensity–flame length relationship (Byram 1959; Alexander and Cruz 2012). From the air, flame length is difficult to assess, so the AAOs describe fire behaviour qualitatively using fire rank, the categories of which capture the state of fire behaviour in terms of its vigor of spread on the surface or the extent of torching and crowning exhibited by the spreading fire. With the fuel type the fire is burning through also observable from the air, this observed rank can be leveraged to estimate intensity of the spreading fire during suppression.

The FBP System includes a quantitative attribute, crown fraction burned (CFB), representing the proportion of crowning expected based on fuel type and surface fire intensity. In conifer forests, the qualitative differences

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

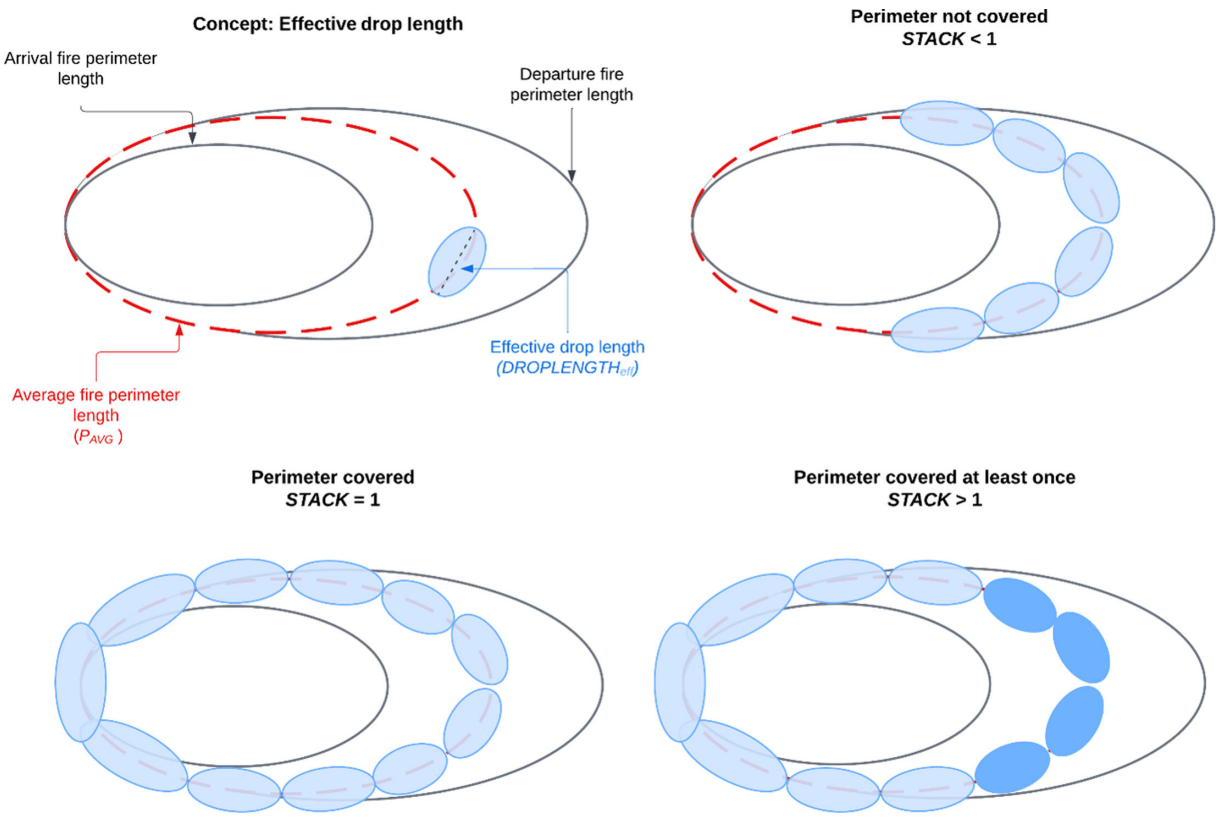

Fig. 2. Diagram illustrating the calculation of the amount of drop stacking variable, $STACK$. $STACK$ is calculated as the ratio of the total number of drops delivered during the mission to the number of drops required to cover the entire perimeter once $STACK < 1$ indicates that the entire perimeter was not covered by drops. $STACK = 1$ indicates that the entire perimeter was covered once in its entirety, and $STACK > 1$ indicates that the perimeter was covered more than once.

between Ranks 3, 4 and 5 correspond to different CFB ranges and, although there is no definitive direct association between CFB value and rank, the qualitative descriptions of fire rank categories (British Columbia Wildfire Service 2025) can be associated with approximate CFB ranges. Table 1 summarises the CFB values assigned to each fire rank and the reasoning for each assignment. Rank 1 and 2 fires are associated with a CFB of 0, as both represent fire behaviour below the threshold for crown fire initiation. The midpoint of the intermittent crowning CFB range (0.1–0.5) was chosen to represent Rank 4, and a CFB of 0.8 was assigned to Rank 5 fires to reflect the upper range of the transition to active crowning.

Using the FBP fuel type at the fire perimeter and the observed fire rank, we estimated a fireline intensity associated with observed fire behaviour (Fig. 1). This calculation applies Byram's fireline intensity, I_B, (Byram 1959) equation:

$$I_B = H \times w \times r$$

where H is the heat of combustion (18,000 kJ/kg), w is the fuel consumed (kg/m^2) and r is the rate of spread (m/s). Heat of combustion is assumed constant in the FBP System; thus, two attributes must be estimated: total fuel consumption and rate of spread. Total fuel consumption (TFC) summarises surface fuel consumption (SFC, calculated from FBP System models using FFMC for C-1 fuels and BUI for other fuel types) and crown fuel consumption, which is calculated as the product of CFB and the crown fuel load, an attribute associated with each fuel type. Using attributes from the FBP System fuel types, the critical surface intensity (CSI) for each fire can be estimated. This value indicates the surface fire intensity above which the fire front will begin to spread upward through the crowns of individual trees, and is based on the fuel type's canopy base height and foliar moisture content; for this analysis, we assume foliar moisture content was a constant 100%, a value that is a compromise between spring dip foliage moisture content values and later summertime levels. Then, using the SFC and CSI, the critical rate of spread for crown fire initiation (RSO) can be estimated. RSO represents the rate of spread (ROS) at which torching can begin, and therefore the point where CFB begins to increase from 0. The final ROS is calculated using the RSO and CFB estimated from the rank observation for each fire. The headfire intensity is then a combination of ROS and

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

Table 1. Crown fraction burned (CFB) values assigned to each fire rank category and the rationale for each. Fire rank descriptions are from British Columbia Wildfire Service (2025).

Fire rank	Fire rank description	CFB range	Assigned CFB
1	Smouldering ground fire; no flaming spread	0	0
2	Surface fire spreading below critical rate for crown fire initiation	0	0
3	Moderately vigorous surface fire with some candling; flame front beginning to reach crown fuels	0–0.1	0.1
4	Moderate torching; intermittent crowning above crown fire initiation threshold but below active crown fire spread	0.1–0.5	0.25
5	Continuous crown fire	0.5–0.9	0.8

the TFC. Rank 1 fires (where CFB = 0) are associated with a head fire intensity of 10 kW/m, representing an accepted upper intensity limit value for fires unable to maintain a sustainable flaming fire front and mostly exhibiting smouldering behaviour. A fire classed as Rank 2 by the aerial observers could be spreading at rates up to but less than the critical spread rate for crowning (RSO). A fire classified as Rank 3 (where CFB = 0.1) where torching and extension of the flames into the crown fuels exists, will have a ROS greater than the RSO.

Fires classified as burning in C-5 fuels (n = 103) were reclassified as C-3 owing to the structure of northern Ontario's natural red and white pine forests, where understorey regeneration can reduce the effective gap between surface and crown fuels below that associated with the FBP System fuel type and can exhibit considerable extended vertical flame front development. This adjustment prevented inflated fire intensity estimates for Rank 3 fires using our CFB-based estimation method; calculated intensities in C-5 fuels at the onset of torching can exceed 15,000 kW/m owing to the large height to live canopy base associated with this FBP fuel type.

Proportion of fireline intensity around the perimeter

The elliptical growth assumption used in fire growth modelling assumes that spread rate varies around the perimeter of the ellipse; therefore, intensity can also be expected to vary similarly. Although the primary outputs of the FBP System are head fire spread rate and intensity, the System also provides a method for estimating spread rate and intensity around the perimeter (Wotton *et al.* 2009). Using each fire's estimated pre-suppression head fire intensity, we summarised (Table 2) the proportion of that fire's perimeter spreading in each of the standard FBP System's intensity classes (Taylor and Alexander 2018).

Effective drop length

The total physical drop length of a CL-415 airtanker is approximately 140 m, and 80 m for a Twin Otter (McFayden *et al.* 2023); however, it would be incorrect to assume this entire drop footprint reaches the forest floor and is effective at reducing flaming on the fireline. Increased intensity requires increased water depth to be effective, and water distribution within a drop is variable, with the greatest depth occurring near the centre of the footprint, while the edges receive less water (McFayden *et al.* 2023). Consequently, depending on a fire's intensity, only a portion of the drop length delivers sufficient water to reduce fire behaviour to a smouldering state. To account for this, we used an estimate of effective drop length from the airtanker energetics model in McFayden *et al.* (2023). This model describes drop patterns from both Twin Otter and CL-415 airtanker and provides estimates of the water coverage level needed to reduce varying fireline intensities to a smouldering state for 1 h. For our analysis, we used the effective drop lengths for different fire intensity classes from these two airtankers in a C-2 closed canopy boreal spruce stand, a common fuel type in Ontario (Table 3).

Calculation of suppression effort

The calculation of suppression effort was designed to approximate how skimmer airtanker operations are conducted in practice. During IA, skimmer airtankers typically begin working on a defined portion of the fire perimeter, placing drops in a sequence and often layering them (or 'stacking') to ensure the line holds and prevents further spread. As suppression progresses, airtankers continue along the perimeter, applying additional drops while the fireline may still be growing. To capture this complex operational practice for this analysis, we defined a suppression effort metric called *STACK*, which quantifies the degree of drop layering (or stacking) relative to the fire perimeter length. *STACK* is calculated as the ratio of the total number of drops delivered during the mission to the number of drops required to cover the entire perimeter once, based on the effective drop length for the airtanker type and fire intensity class. This scaling factor ensures that suppression effort accounts for both perimeter length and drop effectiveness. A *STACK* value less than 1 indicates that the entire perimeter was not covered, and therefore, no stacking of drops is assumed. When *STACK* = 1, this means that the entire perimeter was assumed to be covered once. When *STACK* > 1, the perimeter was assumed to have been covered the number of times of the *STACK* value (Fig. 2).

Because fire intensity varies around the perimeter, we assumed airtankers began suppression at the head of the fire, where fire intensity is highest, and worked around

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

Table 2. The theoretical proportion of an elliptical fire perimeter at intensity Class 2 through 5 given a range of head fire intensity values. These are calculated using FBP System models and the boreal spruce (C-2) fuel type. The ellipse is assumed to have a length-to-breadth ratio of 2.0 (i.e. an elliptical eccentricity of 0.87).

Head fire intensity (kW/m)	Proportion of perimeter at intensity class[A]			
	2	3	4	5
100	1.00	0.00	0.00	0.00
250	1.00	0.00	0.00	0.00
500	0.96	0.04	0.00	0.00
750	0.61	0.39	0.00	0.00
1250	0.43	0.57	0.00	0.00
2000	0.33	0.63	0.04	0.00
2500	0.28	0.44	0.28	0.00
3000	0.25	0.39	0.36	0.00
4000	0.18	0.34	0.44	0.04
7000	0.00	0.39	0.18	0.43

[A]Intensity Class as defined by the FBP System (Taylor and Alexander 2018): IC1, 0–10 kW/m; IC2, 10–500 kW/m; IC3, 500–2000 kW/m; IC4, 2000–4000 kW/m; IC5, 4000–10,000 kW/m. Note that with a head fire intensity of IC2 or greater, none of the perimeter is assumed to be at IC1.

Table 3. Effective drop lengths for the Twin Otter and CL-415 airtanker for fire intensity Classes 2 through 5 in C-2 (boreal spruce) fuels. Effective drop lengths are taken from McFayden *et al.* (2023) and represent the length of the portion of the tanker's drop footprint with enough water coverage (depth of water) to reduce fire behaviour to a smouldering state for ~1 h.

Fireline intensity class[A]	Fireline intensity range (kW/m)	Effective drop length (m)	
		Twin Otter	CL-415
2	10–500	40	90
3	500–2000	20	70
4	2000–4000	6	50
5	4000–10,000	6[B]	30

[A]Effective drop lengths for intensity Class 1 are not presented owing to fires exhibiting Rank 1 fire behaviour being removed from the analysis; the proportion of fireline at each intensity class calculation does not assume any of the fireline is at this minimal level of fire behaviour.
[B]There is technically no effective drop length for the Twin Otter in intensity Class 5 – owing to the width of the drop footprint and the flame front depth for intensity Class 5 fires, the fire is expected to breach all drops. We assumed an effective drop length of 6 m, recognising that the fireline will likely breach the drop.

the perimeter towards lower-intensity areas. The calculation incorporates the proportion of perimeter within each intensity class and the estimated perimeter length (P_{AVG}) to approximate the number of times the perimeter was 'circled' during suppression (Fig. 2). We acknowledge that, in practice, airtanker operations are complex and situationally dynamic and suppression on high-intensity fires often focuses on the head and active portion of the flanks rather than the entire perimeter; however, this simplified framework provides a consistent representation of suppression effort across missions.

Intensity-reduction models

Recall that suppression effectiveness, or the impact of airtanker suppression on reduction in fire intensity, was modelled for both the Twin Otter and CL-415 airtankers using a proportional odds ordinal logistic regression framework where the probability of a given $RANK_{POST}$, or end state of the fire, is modelled as a function of the $RANK_{PRE}$ and amount of suppression, or $STACK$.

The intensity-reduction model for the Twin Otter can be written as:

$$P(Y > K) = \frac{e^{-(\beta_{K0} - \beta_1 RANK_{PRE}(3) - \beta_2 RANK_{PRE}(4) - \beta_3 STACK)}}{1 + e^{-(\beta_{K0} - \beta_1 RANK_{PRE}(3) - \beta_2 RANK_{PRE}(4) - \beta_3 STACK)}}$$

where $RANK_{PRE}$ is a categorical variable with three different levels ($RANK_{PRE} = 2, 3, \text{or } 4$), $RANK_{PRE} = 2$ being the reference category for modelling, therefore not represented in the formula above.

The intensity-reduction model for the CL-415 can be written as:

$$P(Y > K) = \frac{e^{-(\beta_{K0} - \beta_1 RANK_{PRE}(3) - \beta_2 RANK_{PRE}(4) - \beta_3 RANK_{PRE}(5) - \beta_4 STACK)}}{1 + e^{-(\beta_{K0} - \beta_1 RANK_{PRE}(3) - \beta_2 RANK_{PRE}(4) - \beta_3 RANK_{PRE}(5) - \beta_4 STACK)}}$$

where $RANK_{PRE}$ is a categorical variable with four different levels ($RANK_{PRE} = 2, 3, 4, or\ 5$).

Note that owing to operational restrictions,[3] the Twin Otter did not have any observations in the $RANK_{PRE} = 5$ category.

Because the estimation of intensity from observed rank is more challenging in fuels where higher intensities do not manifest as torching and crowning, only fires that were burning in standing conifer fuels were included in the analysis (i.e. all fires occurring in grass, slash, or deciduous fuels were removed). Fires greater than 25 ha in size when air attack arrived were removed to eliminate situations in which the mission objective might have been to suppress only a segment

[3]The OMNR will refrain from dispatching the Twin Otter aircraft to very high intensity fires (i.e. Rank 5) because these fires are too intense and the atmosphere is too turbulent for these aircraft to drop directly into the combustion zone (McFayden *et al.* 2023).

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

of an active fire perimeter. Because of the ordinal analysis framework, all fires that on arrival were observed to be at the lowest rank category (i.e. Rank 1) were removed; in the data, none of these fires were recorded as increasing in rank. The proportional odds assumption (i.e. that each predictor variable has a similar effect on the level of K) was assessed using the Brant–Wald test (Brant 1990) for both models to ensure it held. Model goodness of fit was evaluated using the Lipsitz test (Lipsitz *et al.* 1996), where the observed versus fitted outcomes are divided into equal groups and compared using a chi-square test, with the null hypotheses being that there is no difference between observed and predicted values. All statistical modelling was conducted using the R programming language (R Core Development Team 2023), with the ordinal logistic regression models developed using the MASS package (Venables and Ripley 2002).

Results

After filtering for fires actioned exclusively by Twin Otter or CL-415 airtankers, with a size less than or equal to 25 ha at airtanker arrival, fires burning in standing conifer fuels, and complete pre- and post-suppression fire rank observations, 174 fires remained in the Twin Otter dataset and 1803 in the CL-415 dataset (Fig. 3). Most IA missions were conducted by the CL-415 airtankers, reflecting their greater availability and suppression capacity, whereas Twin Otters were used more frequently in the eastern portion of the province, where they are often positioned on alert. The number of airtankers on each mission varied. For the CL-415 airtanker missions, between one and five airtankers were on each mission for IA suppression, with half of the missions having two CL-415 airtankers working in a circuit. For the Twin Otter airtanker missions, between one and six airtankers were on each mission, with half of the missions having two to three aircraft working in a circuit.

Approximately 90% of fires receiving airtanker suppression were classified as Rank 2 or 3 on arrival, with 80% of all fires being reduced to Rank 1 following suppression. The distribution of the response variable $RANK_{POST}$ was strongly skewed towards lower ranks (Fig. 4), with approximately 80% of fires reduced to Rank 1 following suppression. The cumulative log–log link was therefore used in modelling rather than the default logit link, as the log–log link is better suited to ordinal responses where the probability of lower categories greatly exceeds that of higher categories (Agresti 2002). Table 4 summarises fire size, arrival perimeter, number of drops and drop stacking for each $RANK_{POST}$ category for both the Twin Otter and CL-415 datasets. Approximately half of all fires were actioned at ≤ 1 ha, reflecting the ability of aerial suppression resources to respond quickly to fires while they are still small; size at the start of air attack was seen to increase with the observed rank at the start of suppression ($RANK_{PRE}$).

As expected, the number of drops generally increased on missions that ended with a higher $RANK_{POST}$, reflecting the greater difficulty of suppressing fires with more extreme fire behaviour. Logically, a fire with a higher rank at the end of a mission required more drops simply because this fire had more extreme fire behaviour at the beginning of the mission and the goal of a typical mission is to continue to carry out suppression to reduce fire behaviour as much as possible. However, when suppression effort is expressed by $STACK$, which accounts for perimeter length and effective drop coverage, the pattern is reversed; the median generally increases as $RANK_{POST}$ decreases. For example, for fires actioned by the CL-415 airtanker with a $RANK_{POST}$ of 4, indicating very active fire behaviour at the end of a mission, the median is 0.9, which indicates that the perimeter was too large for the airtankers to 'wrap' the entire fire when accounting for much shorter effective drop length associated with higher intensities. In comparison, a fire with a $RANK_{POST}$ of 1, indicating minimal fire behaviour at the end of a mission, has a median of 2.5, meaning that on average, the perimeter is wrapped at least two times.

Twin Otter model

The model satisfied the proportional odds assumption using the Brant–Wald test ($\chi^2 = 0.91$, d.f. $= 3$, $P = 0.82$) and demonstrated goodness of fit using the Lipsitz test ($\chi^2 = 11.44$, d.f. $= 9$, $P = 0.25$). Model coefficients, standard error and associated P-values are displayed in Table 5. The negative coefficient for $STACK$ indicates the expected physically logical relationship; as drop stacking or layering decreases, the probability of a higher rank after suppression increases. This effect can be seen in Fig. 5, where the probability of the lowest level of fire behaviour, $RANK_{POST} = 1$, increases for all $RANK_{PRE}$ levels as increases. The probability of a $RANK_{POST} = 2$ decreases as $STACK$ increases, but this is merely due to the increasing probability of $RANK_{POST} = 1$ (which implies that by default the other ordinal outcomes must decrease). As the fire rank on arrival increases, the probability of post-suppression Rank 1 fire decreases; this result is consistent with logic that suggests that severe fire behaviour would make it more challenging to reduce the flames to a smouldering state. For example, with the Twin Otter aircraft, a Rank 4 fire, a fire exhibiting intermittent crowning at the start of a mission, has less than a 5% probability of being reduced to a smouldering state if airtankers were to build suppression line around

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

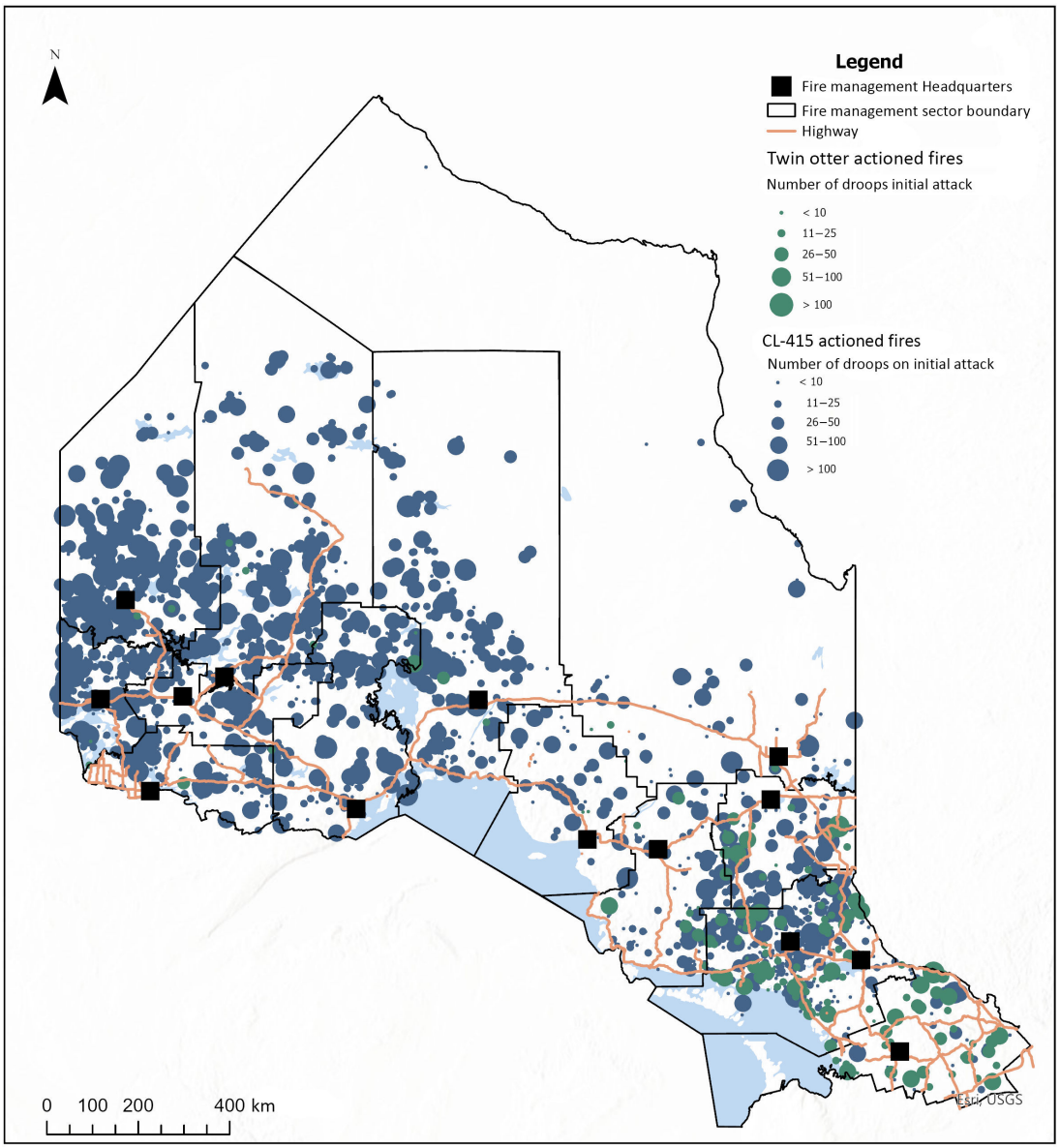

Fig. 3. Ontario fire management area with locations of all fires (n = 1977) used in the analysis displayed according to the airtanker type used for suppression and the number of drops applied on IA. The black boundaries indicate the fire management sector boundaries. The black squares represent Fire Management Headquarters locations from which suppression resources may be dispatched.

the entire perimeter with single drops only; to achieve a greater than 50% probability of leaving the fireline at Rank 1, the model suggests seven or more stacked drops would be needed around the entire perimeter if such drops could be done within the operational safety limits of the aircraft.

Canadair CL-415 model

The proportional odds assumption, which requires that each predictor variable has a consistent effect across all cumulative thresholds of the ordinal response, was assessed using the Brant–Wald test (χ^2 = 19.28, d.f. = 8, P = 0.01). Although the omnibus test was significant, variable-level tests indicated no individual predictor violated the assumption (all $P > 0.12$), suggesting the omnibus result may reflect the sensitivity of the test to the large sample size (n = 1803) rather than a meaningful violation. The model demonstrated goodness of fit using the Lipsitz test (χ^2 = 1.83, d.f. = 9, P = 0.99). Similarly to the Twin Otter model, the negative coefficient for $STACK$ indicates that as more suppression is applied, the probability of reducing fire behaviour to a minimal state continuously increases. The positive coefficient for $RANK_{PRE}$ indicates

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

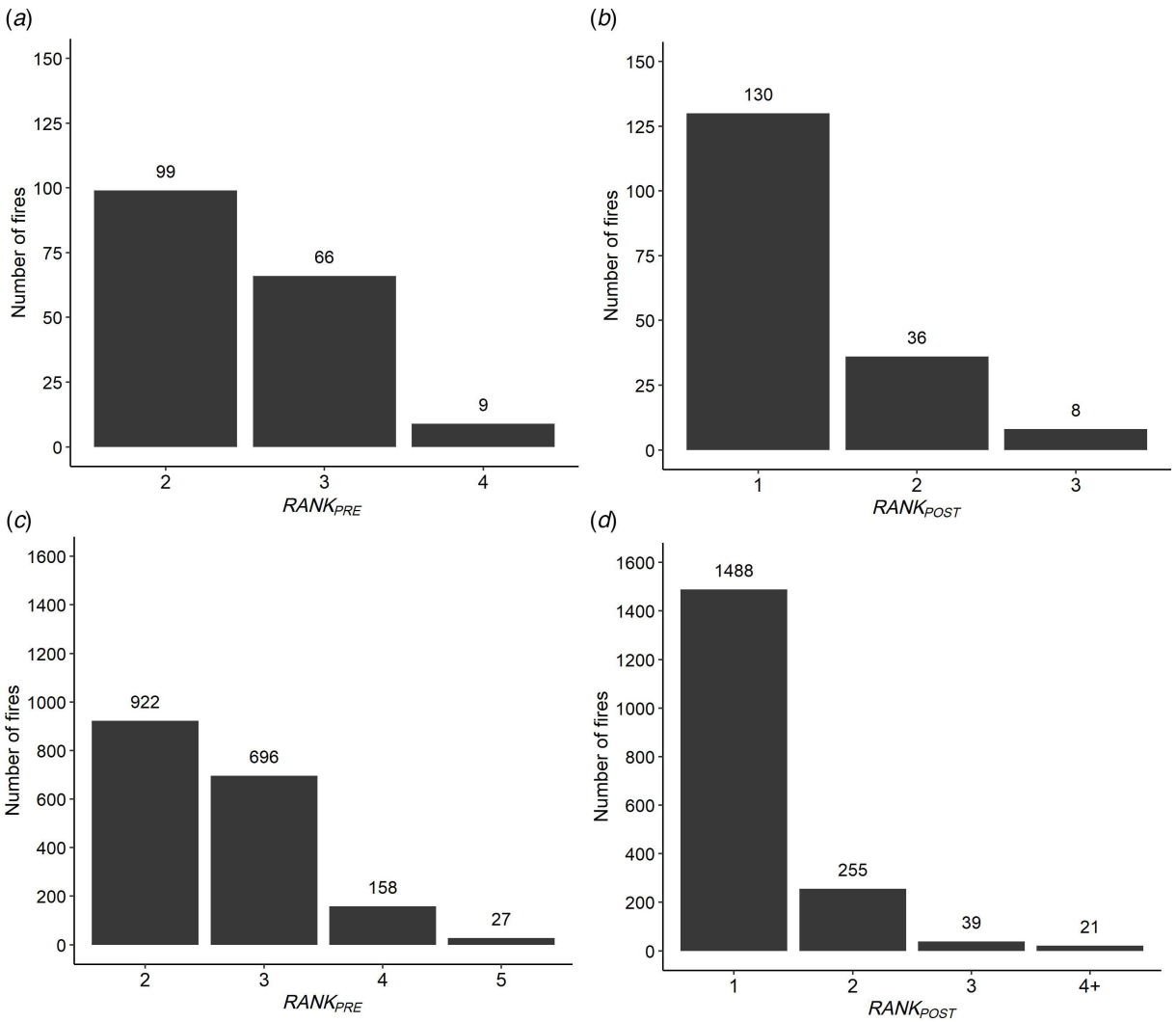

Fig. 4. Number of fires in each of the $RANK_{PRE}$ and $RANK_{POST}$ categories used for ordinal logistic regression modelling for the Twin Otter and CL-415 airtankers: (*a*) Twin Otter $RANK_{PRE}$; (*b*) Twin Otter $RANK_{POST}$; (*c*) CL-415 $RANK_{PRE}$; (*d*) CL-415 $RANK_{POST}$. All fires of $RANK_{POST}$ 4 and greater are combined into a single grouping of '4+' to ensure enough observations were included in the model.

that as the initial fire behaviour increases, the probability of reducing fire behaviour to a minimal state decreases, a finding that reflects the escalating difficulty in suppressing fires when flames start extending into the canopy of the trees. Fig. 6 shows the probability of differing $RANK_{POST}$ states as a function of the suppression effort for the CL-415 airtanker. For the same Rank 4 fire used in the Twin Otter example above, exhibiting intermittent crowning fire behaviour, now with suppression from a CL-415 airtanker, there is a 20% probability of reducing the fire to a smouldering state if the airtankers build line around the perimeter once. On this same fire, to achieve a greater than 50% probability of leaving the fire in a smouldering state, the model suggests five or more stacked drops would be needed around the entire perimeter.

CL-415 upper limit of effectiveness

A commonly cited threshold in fire management in Canada is that direct attack from airtankers is no longer effective once fireline intensity exceeds 4000 kW/m. The model results displayed in Fig. 6 suggest that suppression efforts from the CL-415 airtanker can reduce fire behaviour from Rank 5, which would be associated with fire intensities above 4000 kW/m, to a state of smouldering, or Rank 1. Here, we see that the probability of a fire resulting in a Rank 1 state after 'ringing' the perimeter once is 6%,

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

Table 4. Median and standard deviation (in parentheses) of fire size at IA, arrival perimeter, number of drops and $STACK$ for each ordinal response category for the Twin Otter and CL-415 airtanker.

		$RANK_{POST}$			
		1	2	3	4 +
Twin Otter		$n = 130$	$n = 36$	$n = 8$	
	Fire size at IA (ha)	0.50 (2.44)	3.00 (7.33)	8.50 (5.08)	
	Arrival perimeter (m)	273 (261.81)	669 (512.69)	1122 (417.21)	
	Number of drops	19 (18.97)	29 (26.10)	29 (13.40)	
	$STACK$	3.01 (2.92)	1.86 (1.54)	1.52 (2.41)	
CL-415		$n = 1488$	$n = 255$	$n = 39$	$n = 21$
	Fire size at IA (ha)	1.00 (3.96)	3.00 (7.13)	8.50 (7.21)	10.00 (7.05)
	Arrival perimeter (m)	386 (353.79)	669 (514.21)	1127 (477.01)	1222 (454.23)
	Number of drops	14 (21.39)	22 (34.80)	37 (34.35)	42 (42.10)
	$STACK$	2.51 (2.50)	1.91 (2.28)	1.75 (1.82)	0.86 (1.89)

Table 5. Proportional odds ordinal logistic regression model results. For the Twin Otter, $n = 174$ observations were used to fit the model. For the CL-415, $n = 1803$ observations were used to fit the model. The response variable is rank of fire after airtanker suppression: Rank 1, Rank 2, Rank 3, or Rank 4+ (for CL-415 model). The reference category for $RANK_{PRE}$ is 2.

	Variable	Coefficient	s.e.	*P*-value
Twin Otter	Intercept (Rank 1 | Rank 2)	1.47	0.38	<0.001
	Intercept (Rank 2 | Rank 3)	3.55	0.51	<0.001
	$RANK_{PRE}$			
	$RANK_{PRE} = 3$	1.56	0.37	<0.001
	$RANK_{PRE} = 4$	2.95	0.52	<0.001
	$STACK$	−0.26	0.09	<0.001
CL-415	Intercept (Rank 1 | Rank 2)	2.40	0.16	<0.001
	Intercept (Rank 2 | Rank 3)	4.29	0.20	<0.001
	Intercept (Rank 3 | Rank 4+)	5.40	0.26	<0.001
	$RANK_{PRE}$			
	$RANK_{PRE} = 3$	1.60	0.16	<0.001
	$RANK_{PRE} = 4$	3.12	0.18	<0.001
	$RANK_{PRE} = 5$	3.62	0.27	<0.001
	$STACK$	−0.22	0.03	<0.001

and this probability increases to over 50% only after eight circuits of drops are made around the entire perimeter. Moreover, the model indicates a reasonable probability of reducing such fires to Rank 2, where flames have been reduced to sizes manageable for ground crew suppression. We explored this result further to ensure it was not an artifact of the modelling by examining the pre- and post-suppression fireline intensity relationship between all fires actioned by the CL-415 airtanker (Fig. 7). Although suppression is expected to reduce fire intensity, a small number of observations fall above the line of perfect agreement, indicating cases where the estimated post-suppression fire intensity exceeded the pre-suppression intensity. These cases likely reflect the large number of factors that can influence fire behaviour; changes in fuel type, fuel moisture, or even a fire's acceleration to a quasi- equilibrium state, could result in increasingly severe fire behaviour independently of suppression effort. These data do however suggest that there are observed cases where suppression from the CL-415 airtanker has reduced fireline intensity from levels above 4000 kW/m (and exhibiting considerable crowning) to a level where ground crews may be able to action the fire, an intensity of less than 2000 kW/m. These findings suggest that there is potential for suppression success even with more active fire behaviour, and although further research is needed, the intensities estimated for these Rank 5 fires suggest that perhaps a fireline intensity of 10,000 kW/m may be a more realistic upper limit to suppression effectiveness.

Discussion

This study developed empirical models of airtanker suppression effectiveness using 17 years of operational observations recorded by AAOs. Unlike previous analyses focused on aerial suppression influence on IA success or containment outcomes (e.g. Plucinski 2012; Calkin *et al.* 2014; Wheatley *et al.* 2022; Rezaei *et al.* 2023), our work

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

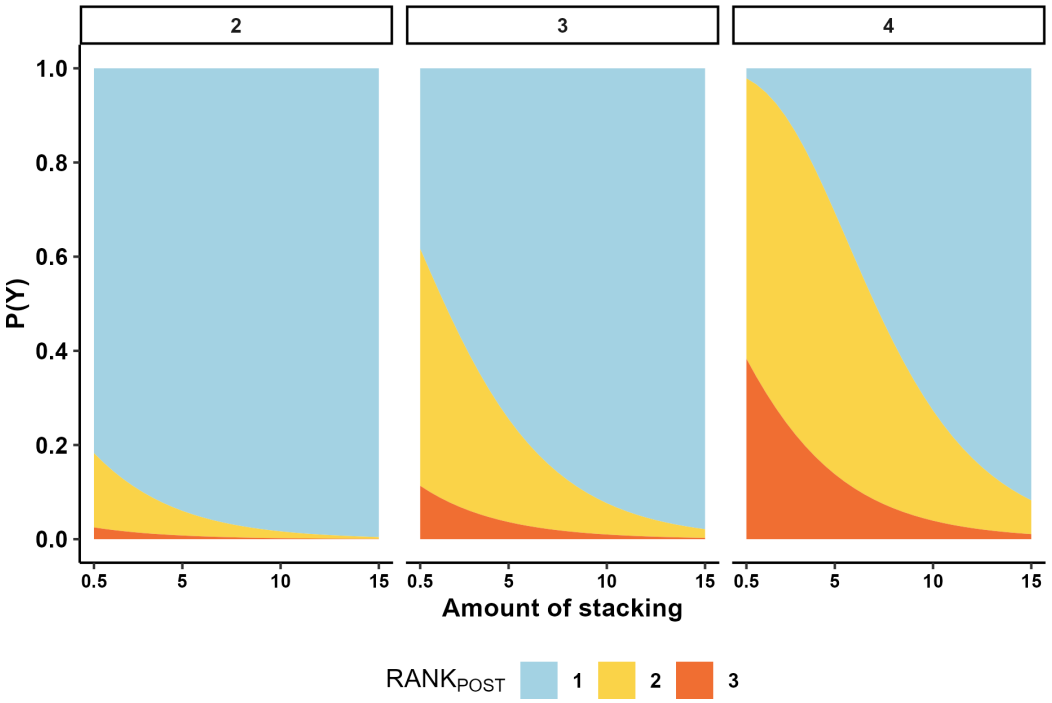

Fig. 5. Probability of a given $RANK_{POST}$ outcome, P(Y), as a function of the amount of stacking (i.e. the number of times the entire perimeter is 'ringed' with airtanker drops) for the Twin Otter airtanker. Each panel represents a different $RANK_{PRE}$, ranging from 2 through 4. In this stacked area plot, the boundary between adjacent coloured regions represents the cumulative probability curve for each outcome. The width of each coloured band at any given stacking value directly represents the probability of that $RANK_{POST}$ outcome. For example, in the $RANK_{PRE}$ = 4 panel, the width of the orange (Rank 3) band at a stacking value of 0.5 represents approximately a 40% probability of ending at Rank 3, while the width of the blue (Rank 1) band at a stacking value of 15 represents a probability approaching 90% of being reduced to a smouldering state.

quantified the conditional probability of fire behaviour reduction given observed suppression effort. The qualitative indicator of fire rank was used as an operational proxy for fire intensity, allowing suppression effectiveness to be evaluated in terms directly relevant to tactical decision-making. The models demonstrate a physically logical pattern that has not been demonstrated by previous statistical analyses of historical suppression data (e.g. Calkin *et al.* 2014; Tremblay *et al.* 2018; Wheatley *et al.* 2022): the probability of reducing a fire to a smouldering state increases with greater suppression effort, represented by the amount of drop layering (or stacking) around the fire perimeter. By developing separate models for Ontario's two skimmer airtankers, the Canadair CL-415 and the DHC-6 Twin Otter, this research provides insight into how these aircraft are used operationally and their relative capacity to reduce fire behaviour to levels that are safe and manageable for ground suppression and containment.

The development of two separate intensity-reduction models for the CL-415 and the Twin Otter allowed direct comparison of observed airtanker effectiveness (Table 5). Regardless of initial fire behaviour, fewer drops were required from CL-415 airtankers than Twin Otters to achieve similar reductions in fire behaviour, reflecting the larger drop volumes and greater effective coverage of the CL-415. For lower-intensity spreading surface fires (Rank 2), the CL-415 exhibited up to a 10% higher probability of reducing fire behaviour to a smouldering state, with differences decreasing after approximately three passes around the fire perimeter. As the initially observed fire behaviour increased in severity, differences between the two aircraft became more evident. For Rank 3 fires, the CL-415 had up to a 25% higher probability of achieving a post-mission smouldering state at lower levels of stacking, with effectiveness converging with the Twin Otter after approximately eight perimeter passes (Figs 5 and 6). For Rank 4 fires, the CL-415 maintained approximately a 20% higher probability of reducing fire behaviour to Rank 1, with convergence with the Twin Otter after approximately 10 passes. These results indicate that aircraft differences are most operationally relevant at higher severity of fire behaviour, suggesting that, when airtanker availability is constrained, prioritising larger skimmer airtankers on higher-intensity fires may increase the probability of

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

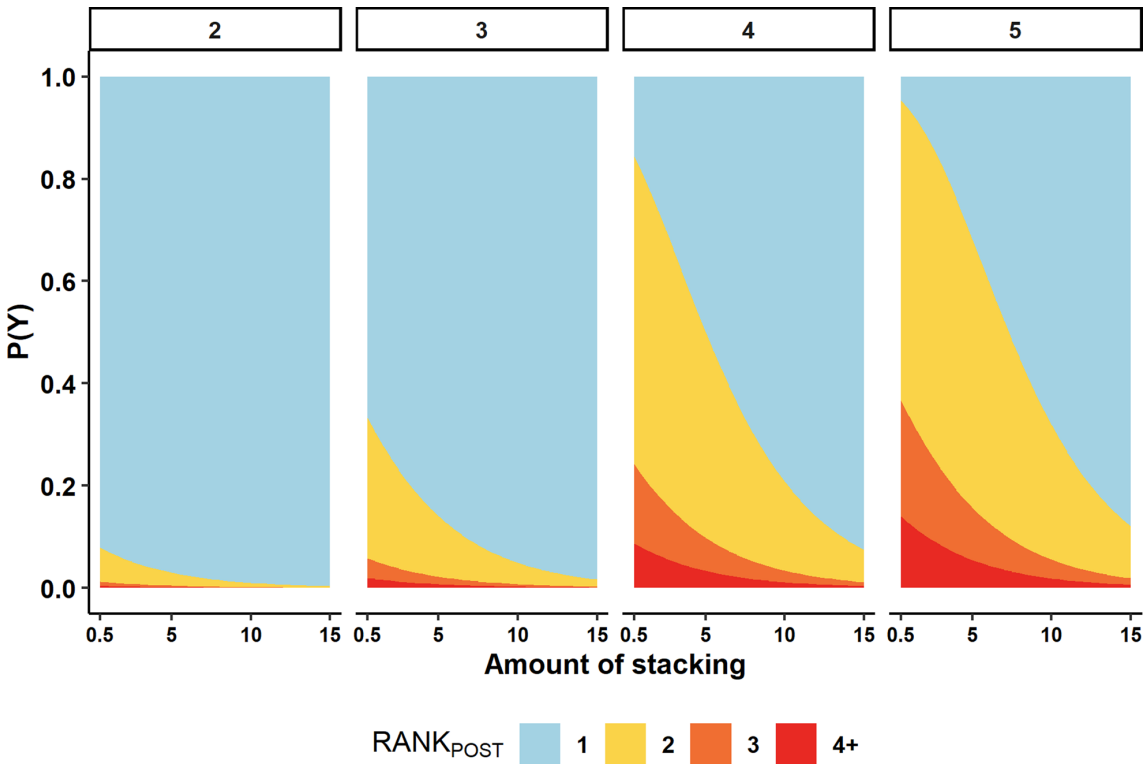

Fig. 6. Probability of a given $RANK_{POST}$ outcome, P(Y), as a function of the amount of stacking (i.e. the number of times the entire perimeter is 'ringed' with airtanker drops) for the CL-415 airtanker. Each panel represents a different $RANK_{PRE}$, ranging from 2 through 5. In this stacked area plot, the boundary between adjacent coloured regions represents the cumulative probability curve for each outcome. The width of each coloured band at any given stacking value directly represents the probability of that $RANK_{POST}$ outcome. For example, in the $RANK_{PRE}$ = 4 panel, the width of the yellow (Rank 2) band at a stacking value of 0.5 represents approximately a 60% probability of ending at Rank 2, while the width of the blue (Rank 1) band at a stacking value of 15 represents a probability approaching 90% of being reduced to a smouldering state.

achieving meaningful fire behaviour reduction and improving containment opportunities.

Although this study provides some of the first empirical statistical models of fire behaviour reduction for skimmer airtankers in the Canadian boreal forest, the results can be compared with existing theoretical frameworks, including the airtanker energetics model of McFayden *et al.* (2023) and earlier extinguishment models (e.g. Stechishen and Little 1971; Simard and Young 1978; Loane and Gould 1986) (see Supplementary material Appendix B). At lower fire behaviour levels, the models developed here align closely with theoretical expectations. For example, the CL-415 model predicts that a single drop is often sufficient to reduce a Rank 2 fire to a smouldering state, consistent with the models by McFayden *et al.* (2023) and Loane and Gould (1986). However, as fire behaviour increases to intermittent crowning and active crown fire, the empirical models developed indicate that substantially greater suppression effort is typically applied than theoretical minimums suggest. Under Rank 4 and 5 conditions, the CL-415 models indicate that approximately five to eight stacked drops are required to reach a smouldering state, whereas theoretical models often predict the equivalent of two to three stacked drops based on water depth required to extinguish fire intensities in those conditions (Loane and Gould 1986; McFayden *et al.* 2023).

The divergence between the models developed in this study and those presented above likely reflect the difference between minimum theoretical extinguishment requirements and operational suppression practice. The models developed capture suppression outcomes as they occur under real-world conditions, where drop placement inefficiencies and spatial variation in fuels and fire behaviour are common. In an operational context, fire personnel may deliberately apply suppression effort beyond theoretical minimums to reduce the risk of re-establishment of the combustion zone and increase the likelihood of achieving mission objectives, particularly when aircraft are available, and conditions permit continued use. Across all fire behaviour levels, the empirical models developed here suggest that earlier extinguishment models by Simard and Young (1978) and Stechishen and Little (1971) tend to

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

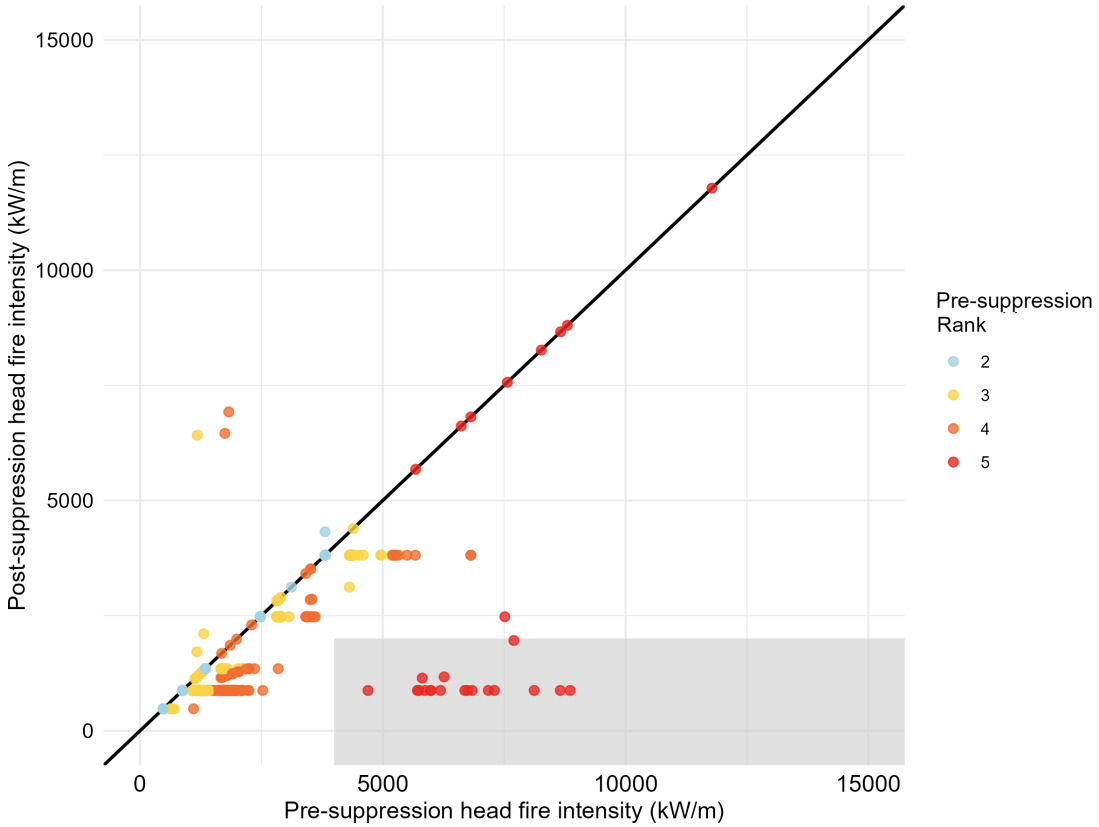

Fig. 7. Pre-suppression and post-suppression head fire intensity as predicted by the Fire Behaviour Prediction (FBP) System using qualitative estimates of fire behaviour from the trained operational staff. Fires included in this figure are only those actioned by the CL-415 airtanker (n = 1803). The solid black indicates the line of perfect agreement. The grey shaded box highlights those fires that were estimated to have pre-suppression fireline intensity above 4000 kW/m and post-suppression fireline intensity is below 2000 kW/m.

over-predict required water depths required for extinguishment, whereas both McFayden *et al.* (2023) and Loane and Gould (1986) appear to under-predict suppression effort as fire severity behaviour increases. These findings underscore the importance of integrating empirical operational data with theoretical models to more accurately represent real-world aerial suppression effectiveness.

This research has direct implications for operational decision support systems including airtanker dispatch optimisation (e.g. Wei *et al.* 2015, 2020) and fire growth and burn probability modelling (e.g. Parisien *et al.* 2019; Boychuk *et al.* 2020). By quantifying the probability of achieving reduced fire behaviour as a function of suppression effort, aircraft type and starting fire rank, the models provide empirically grounded effectiveness parameters that can inform prioritisation when airtanker resources are limited. Rather than treating suppression effectiveness as a binary indicator, the results offer a probabilistic estimate of expected suppression outcomes that can be incorporated into dispatch optimisation frameworks and scenario-based planning tools. Similarly, integrating suppression dynamics such as airtanker line building into fire growth and burn probability models would represent a significant advancement in decision support capability over current approaches (e.g. Noonan-Wright *et al.* 2011; McFayden *et al.* 2025), which typically lack automated suppression components.

An important observation from this study is that suppression by CL-415 airtankers was sometimes associated with reductions in estimated fire intensity from above 4000 kW/m to below 2000 kW/m. These observations challenge the conventional thresholds suggesting that direct suppression becomes ineffective beyond a head fire intensity of 4000 kW/m and indicate that fire behaviour reduction may be possible as intensities approach 10,000 kW/m under certain conditions. These findings should not be interpreted as justification for revising operational guidelines (e.g. Taylor and Alexander 2018) at this stage. Rather, they highlight the need for targeted field experiments (e.g. Loane and Gould 1986; Plucinski 2010; Wheatley *et al.* 2024) and further analysis of fire behaviour and suppression operational datasets (e.g. United States Department

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

of Agriculture 2020; Simpson *et al.* 2022; Plucinski 2025; Wiard-Greene *et al.* 2025; Young *et al.* 2025) to refine suppression effectiveness thresholds across fuel types and fire environments. Such work would improve predictive models and inform decision-support tools for airtanker dispatch under extreme fire behaviour conditions, where the probability of success may be low and operational risk is elevated (Stonesifer *et al.* 2021).

Several limitations should be acknowledged. The conceptual framework assumed that airtankers worked the entire fire perimeter, which may not reflect operational reality, particularly on larger or higher-intensity fires where suppression often focuses on the head and adjacent flanks. Although this assumption influences the magnitude of the amount of stacking, it does not alter the observed relationship between suppression effort and fire behaviour reduction. In practice, focusing suppression on a portion of the perimeter would imply even greater localised stacking, reinforcing the conclusion that operational suppression effort often exceeds theoretical minimums. The analysis also did not differentiate between water and foam drops, despite Ontario's operational practice of using both, as data structure limitations precluded drop-level assessment. Future research should explicitly examine the influence of foam and other additives on suppression effectiveness.

Cycle time, the time between water drops, is a factor that could affect the reduction of fire behaviour seen over a mission. Often airtankers work in circuits and they apply suppression drops one after another to decrease the time between water applications, thereby decreasing the ability of the fireline to reheat and spread to unburned adjacent fuels. Although circuit time is not presented in the models above, we considered this attribute by modelling the 'rate of drops' represented by the number of drops applied as a function of mission duration, where we found no evidence to support that the rate airtankers were dropping at was more influential on fire behaviour than the amount of suppression effort alone. This is likely because Ontario has an abundance of readily available waterbodies dispersed across the province from which airtankers can pick up (i.e. the average distance from the fire to the nearest pick-up lake is 5 km); therefore, cycle time does not vary substantially (i.e. average cycle time is 11 drops per hour) (McFayden *et al.* 2023).

We acknowledge that the qualitative observation of fire rank as reported by the AAOs is subject to interpretation bias, given that it is estimated by multiple individuals across many missions. However, fire rank is assessed by highly trained wildfire response personnel who apply standardised criteria when characterising fire behaviour from the air (British Columbia Wildfire Service 2025). The validity of fire rank as a proxy for fire behaviour has been examined using this dataset in previous work, where good agreement was found between AAO observations of fire rank and FBP System predictions of crown fraction burned, using weather observations from nearby stations and the reported FBP fuel type at the fire (Wheatley 2024).

From a broader planning perspective, these findings provide timely empirical evidence relevant to projections that Ontario may need to substantially increase suppression resources to maintain current level of IA containment under a changing fire climate. Wotton and Stocks (2006) estimated that, from the perspective of IA alone, Ontario would have to double its suppression resources by the year 2040 to maintain current levels of IA containment success; this substantial increase in resources just to deal with a modest change in the fire environment. Wotton *et al.* (2017) further showed that with the projected changes in fire climate over the current century, the expected number of days per season that require airtanker support, as defined by fireline intensity-based suppression effectiveness thresholds, will increase by nearly 200% in some areas of the boreal forest. By providing data-driven estimates of the suppression capability of skimmer airtankers, especially the CL-415, this study contributes critical information for evaluating future resource needs, guiding fleet replacement decisions and improving suppression system simulation models such as 'The Level of Protection Analysis System used in Ontario' (McAlpine and Hirsch 1999). Because the CL-415 is among the most widely used skimmer airtankers globally, the models presented here also have relevance beyond Ontario and Canada and can be incorporated into suppression simulation frameworks used in other jurisdictions (e.g. Martell *et al.* 1984; Keating *et al.* 2012). This work establishes an empirical foundation for integrating aerial suppression effectiveness into operational planning, predictive modelling and decision support systems.

Supplementary material

Supplementary material can be accessed from the article page online.

References

Agresti A (2002) 'Categorical data analysis.' (John Wiley & Sons: New Jersey)

Alexander ME, Cruz MG (2012) Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height. *International Journal of Wildland Fire* 21(2), 95–113. doi:10.1071/WF11001

Boychuk D, McFayden CB, Evens J, Shields J, Stacey A, Woolford DG, Wotton BM, Johnston D, Leonard D, McLarty D (2020) Assembling and customizing multiple fire weather forecasts for burn probability and other fire management applications in Ontario, Canada. *Fire* 3(2), 16. doi:10.3390/fire3020016

Brant R (1990) Assessing proportionality in the proportional odds model for ordinal logistic regression. *Biometrics* 46(4), 1171–1178. doi:10.2307/2532457

British Columbia Wildfire Service (2025) Wildfire rank. Available at https://www2.gov.bc.ca/gov/content/safety/wildfire-status/wildfire-response/about-wildfire/wildfire-rank. [accessed 21 November 2025]

Brown AA, Davis KP (1973) 'Forest fire: control and use.', 2nd edn (McGraw-Hill). p. 584.

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

Byram GM (1959) Combustion of forest fuels. In 'Forest fire: control and use'. (Ed KP Davis). (McGraw-Hill: New York)
Calkin DE, Gebert KM, Jones JG, Neilson RP (2005) Forest Service large fire area burned and suppression expenditure trends, 1970–2002. *Journal of Forestry* 103(4), 179–183. doi:10.1093/jof/103.4.179
Calkin DE, Stonesifer CS, Thompson MP, McHugh CW (2014) Large airtanker use and outcomes in suppressing wildland fires in the United States. *International Journal of Wildland Fire* 23(2), 259–271. doi:10.1071/WF13031
Collins KM, Price OF, Penman TD (2018) Suppression resource decisions are the dominant influence on containment of Australian forest and grass fires. *Journal of Environmental Management* 228, 373–382. doi:10.1016/j.jenvman0.2018.09.031
Forestry Canada Fire Danger Group (1992) Development of the Canadian Forest Fire Behaviour Prediction System. Information Report ST-X-3 (Forestry Canada, Headquarters, Fire Danger Group and Science and Sustainable Development Directorate, Ottawa). Available at https://ostrnrcan-dostrncan.canada.ca/handle/1845/235421. accessed 16 December 2025
Hanes CC, Wang X, Jain P, Parisien MA, Little JM, Flannigan MD (2019) Fire-regime changes in Canada over the last half century. *Canadian Journal of Forest Research* 49(3), 256–269. doi:10.1139/cjfr-2018-0293
Hanes CC, Jain P, Wang W, Wang X, Parisien MA, Little JM, Flannigan MD (2025) Fire regime changes in Canada: an update. *Canadian Journal of Forest Research* 55, 1–11. doi:10.1139/cjfr-2025-0209
Hansen R (2012) *Corrigendum to*: Estimating the amount of water required to extinguish wildfires under different conditions and in various fuel types. *International Journal of Wildland Fire* 21(6), 778–778. doi:10.1071/WF11022_CO
Hirsch KG, Martell DL (1996) A review of initial attack fire crew productivity and effectiveness. *International Journal of Wildland Fire* 6(4), 199–215. doi:10.1071/WF9960199
Hodgson A, Heislers A (1973) 'Some aspects of the role of forest fire in south-eastern Australia.' (Forests Commission: Victoria)
Hosmer DW, Lemeshow S, Sturdivant RX (2013) 'Applied logistic regression.' (John Wiley & Sons). doi:10.1002/9781118548387
Katuwal H, Hand MS, Thompson M, Stonesifer C, Calkin D (2018) Predict and Attack (or Don't): An Econometric Approach to Large Wildfire Early Detection and Suppression Effectiveness. 2018 Agricultural and Applied Economics Association Annual Meeting, Washington, D.C
Keating EG, Morral AR, Price CC, Woods D, Norton D, Panis C, *et al* (2012) Air attack against wildfires: understanding US Forest Service requirements for large aircraft. Available at https://www.rand.org/pubs/monographs/MG1234.html
Korkola K, Wheatley M, Beverly J, James PMA, Wotton M (2024) A comparative analysis of wildfire initial attack containment objectives and modelling strategies in Ontario, Canada. *International Journal of Wildland Fire* 33(12), 12. doi:10.1071/WF24104
Lipsitz SR, Fitzmaurice GM, Molenberghs G (1996) Goodness-of-fit tests for ordinal response regression models. *Applied Statistics* 45(2), 175–190. doi:10.2307/2986153
Loane IT, Gould JS (1986) 'Aerial suppression of bushfires: cost–benefit study for Victoria.' (National Bushfire Research Unit, CSIRO Division of Forest Research)
Luke RH, McArthur AG (1978) 'Bushfires in Australia.' (Australian Government Publishing Service)
Martell DL, Drysdale RJ, Doan GE, Boychuk D (1984) An evaluation of forest fire initial attack resources. *Interfaces* 14(5), 20–32. doi:10.1287/inte0.14.5.20
McAlpine RS, Hirsch KG (1999) An overview of LEOPARDS: the Level of Protection Analysis System. *The Forestry Chronicle* 75(4), 615–621. doi:10.5558/tfc75615-4
McCarthy GJ (2003) Effectiveness of aircraft operations by the Department of Natural Resources and Environment and the Country Fire Authority 1997–98. Research Report No. 52. Available at https://ffm.vic.gov.au/_data/assets/pdf_file/0010/21061/Report-52-Effectiveness-of-Aircraft-Operations-by-the-Department-of-Natural-Resources-and-Environment-and.pdf. [accessed 15 December 2025]
McFayden CB, Wotton BM, Robinson JW, Johnston JM, Cantin A, Jurko NM, Boucher J, Wheatley M, Ansell M, Boychuk D, Russo B (2023) Reference guide to the drop effectiveness of skimmer and rotary wing airtankers. Canadian Forest Service, Great Lakes Forestry Centre, Information Report GLC-X-35. Available at https://ostrnrcan-dostrncan.canada.ca/handle/1845/218123. [accessed 16 December 2025]
McFayden CB, Boychuk D, Evens J, McLarty D, Stacey A, Leonard D, Shields J (2025) History and overview of research and development for Ontario's FireGUARD decision support system for appropriate response. *The Forestry Chronicle* 101(2), 131–145. doi:10.5558/tfc2025-015
Noonan-Wright EK, Opperman TS, Finney MA, Zimmerman GT, Seli RC, Elenz LM, Calkin DE, Fiedler JR (2011) Developing the US wildland fire decision support system. *Journal of Combustion* 2011(1), 168473. doi:10.1155/2011/168473
Nychka D, Furrer R, Paige J, Sain S (2017) Fields: tools for spatial data. (R package version 10.3). doi:10.5065/D6W957CT
Parisien MA, Dawe DA, Miller C, Stockdale CA, Armitage OB (2019) Applications of simulation-based burn probability modelling: a review. *International Journal of Wildland Fire* 28(12), 913. doi:10.1071/WF19069
Penney G, Habibi D, Cattani M, Carter M (2019) Calculation of critical water flow rates for wildfire suppression. *Fire* 2(1), 3. doi:10.3390/fire2010003
Plucinski MP (2010) Evaluation of the effectiveness of the 10 tanker air carrier DC-10 air tanker, Victoria 2010. Technical Report. Bushfire Cooperative Research Centre, Victoria, Australia.
Plucinski MP (2012) Factors affecting containment area and time of Australian forest fires featuring aerial suppression. *Forest Science* 58(4), 390–398. doi:10.5849/forsci.10-096
Plucinski MP (2019*a*) Contain and control: wildfire suppression effectiveness at incidents and across landscapes. *Current Forestry Reports* 5(1), 20–40. doi:10.1007/s40725-019-00085-4
Plucinski MP (2019*b*) Fighting flames and forging firelines: wildfire suppression effectiveness at the fire edge. *Current Forestry Reports* 5(1), 1–19. doi:10.1007/s40725-019-00084-5
Plucinski M (2025) 'Review of aerial suppression effectiveness research literature.' (Natural Hazards Research Australia)
R Core Development Team (2023) R: A language and environment for statistical computing. R Foundation for Statistical Computing: Vienna, Austria. Available at https://www.r-project.org/ [Accessed 21 November 2025]
Rezaei M, Lee I, Beverly J (2023) The effect of wildfire suppression resources: targeting fire groups with enhanced treatment effect. SSRN. doi:10.2139/ssrn.4554313
Simard AJ, Young A (1978) Airpro: an air tanker productivity computer simulation model: the equations (summary). Canadian Forestry Service, Forest Fire Research Institute. Information Report FF-X-66, Ottawa, Ontario, p. 18.
Simpson H, Storey M, Plucinski M, Price O (2022) Investigating the suitability of aviation tracking data for use in bushfire suppression effectiveness research (Natural Hazards Research Australia). Available at https://www.naturalhazards.com.au/resources/publications/report/investigating-suitability-aviation-tracking-data-use-bushfire [Accessed 22 December 2025]
Stechishen E, Little EC (1971) 'Water application depths required for extinguishment of low intensity fires in forest fuels.' (Forest Fire Research Institute, Department of Fisheries and Forestry: Canada)
Stocks BJ, Mason JA, Todd JB, Bosch EM, Wotton BM, Amiro BD, Flannigan MD, Hirsch KG, Logan KA, Martell DL, Skinner WR (2002) Large forest fires in Canada, 1959–1997. *Journal of Geophysical Research* 107(D1). doi:10.1029/2001JD000484
Stonesifer CS, Calkin DE, Thompson MP, Stockmann KD (2016) Fighting fire in the heat of the day: an analysis of operational and environmental conditions of use for large airtankers in United States fire suppression. *International Journal of Wildland Fire* 25(5), 520–533
Stonesifer CS, Calkin DE, Thompson MP, Belval EJ (2021) Is this flight necessary? The Aviation Use Summary (AUS): a framework for stra-

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026

tegic, risk-informed aviation decision support. *Forests* 12(8), 1078. doi:10.3390/f12081078
Taylor SW, Alexander ME (2018) 'Field guide to the Canadian Forest Fire Behaviour Prediction (FBP) System.' (Canadian Forest Service and BC Ministry of Forests Partnership Agreement on Forest Resource Development)
Tremblay PO, Duchesne T, Cumming SG (2018) Survival analysis and classification methods for forest fire size. *PloS One* 13, e0189860, 1–16. doi:10.1371/journal.pone0.0189860
United States Department of Agriculture (2020) Aerial Firefighting Use and Effectiveness (AFUE) Report (United States Department of Agriculture, Washington, DC). Available at https://www.fs.usda.gov/sites/default/files/2020-08/08,242,020_afue_final_report.pdf
Van Wagner CE (1987) 'Development and structure of the Canadian Forest Fire Weather Index System.' (Forestry Technical Report. Canadian Forest Service: Ottawa, Canada)
Van Wagner CE, Taylor SW (2022) Theoretical amounts of water to put out forest fires. Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-458. Available at https://publications.gc.ca/collections/collection_2023/rncan-nrcan/Fo143-2-458-eng.pdf
Venables WN, Ripley BD (2002) 'Modern applied statistics with S', 4th edn (Springer: New York). doi:10.1007/978-0-387-21706-2
Wei Y, Bevers M, Belval EJ (2015) Designing seasonal initial attack resource deployment and dispatch rules using a two-stage stochastic programming procedure. *Forest Science* 61(6), 1021–1032. doi:10.5849/forsci.14-182
Wei Y, Thompson MP, Belval EJ, Calkin DE, Bayham J (2020) Understand daily fire suppression resource ordering and assignment patterns by unsupervised learning. *Machine Learning and Knowledge Extraction* 3(1), 14–33. doi:10.3390/make3010002
Wheatley M, Wotton BM, Woolford DG, Martell DL, Johnston JM (2022) Modelling initial attack success on forest fires suppressed by air attack in the province of Ontario, Canada. *International Journal of Wildland Fire* 31(8), 774–785. doi:10.1071/WF22006
Wheatley MJ (2024) Forest fire suppression effectiveness in the Canadian boreal forest. Doctoral Dissertation, University of Toronto, Canada
Wheatley M, Ifimov G, Jong M, Naprstek T, Wotton M, Reid R, McFayden C, Leblanc G, Johnston J, Robinson J (2024) How effective is aerial suppression? We need to find out. Canadian Wildland Fire & Smoke Newsletter, Canada Wildfire. Available at https:// www.canadawildfire.org/_files/ugd/90df79_7e49f7f96,579,418e96015 4fe60c6bc19.pdf
Wheatley M, McFayden C, Refai R, Hope E, Simpson H (2025) Canada: aerial suppression effectiveness research. Wildfire Magazine, International Association of Wildland Fire. Available at https://www.iawfonline.org/article/canada-aerial-suppression-effectiveness-research/
Wiard-Greene L, Johnson J, Hogland J, Bunt F, Bova J (2025) Investigating the Impact of Aerial Firefighting on Rate of Wildfire Spread. *Fire* 9(1), 2. doi:10.3390/fire9010002
Wotton BM, Stocks BJ (2006). In 'Fire management in Canada: vulnerability and risk trends'. (Eds K Hirsch, P Fuglem) pp. 49–55. (Canadian Wildland Fire Strategy: Background Synthesis, Analysis, and Perspectives)
Wotton BM, Alexander ME, Taylor SW (2009) Updates and revisions to the Canadian Forest Fire Behaviour Prediction System. Nat. Res. Can., Can. For. Serv. Great Lakes Forestry Centre Info. GLC-10, p. 47.
Wotton BM, Flannigan MD, Marshall GA (2017) Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. *Environmental Research Letters* 12(9), 095003. doi:10.1088/1748-9326/aa7e6e
Young JD, O'Connor CD, Arkowitz A, Orland E, Ritter S, Calkin D, Wadhwani R, Cansler CA (2025) Containment lines, PODs and suppression success: a case study of the 2021 Schneider Springs Fire. *International Journal of Wildland Fire* 34(12). doi:10.1071/WF25124

Data availability. The authors do not have permission to share the data. Summarised data that support the figures and conclusions will be shared on a reasonable request to the corresponding author.

Conflicts of interest. The authors declare that they have no conflicts of interest.

Declaration of funding. This research was partially supported by the Natural Science and Engineering Research Council of Canada (NSERC) through a Canada Graduate Scholarship – Doctoral to the lead author.

Acknowledgements. We gratefully appreciate the helpful advice and comments on the methodology and earlier versions of this manuscript by David Martell (University of Toronto), Douglas Woolford (Western University) and Joshua Johnston (Canadian Forest Service). We also appreciate the conversations about air attack operations in Ontario with Andrew Reid and the OMNR air attack officers.

Author affiliations
[A]Ontario Ministry of Natural Resources, Aviation Forest Fire Emergency Services, Sault Ste Marie, ON P6A 6V5, Canada.
[B]Institute of Forestry and Conservation, John H. Daniels Faculty of Architecture, Landscape and Design, University of Toronto, Toronto, ON M5S 3B3, Canada.
[C]Great Lakes Forestry Centre, Canadian Forest Service, Natural Resources Canada, Sault Ste Marie, ON P6A 2E5, Canada.

Downloaded from connectsci.au/wf/article-pdf/doi/10.1071/WF25311/1973549/wf25311.pdf by Ministry Of Natural Resources user on 29 October 2026