Comparison of forest fire suppression in Quebec and Sweden

A historical review, 1998-2015

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Swedish University of Agricultural Sciences

Master Thesis no. 301

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Cover photo: The Gannett Glacier fire crew battles the Sunrise wildfire near Meadow Lakes, Alaska in May 2016. Photo Credit: Bill Roth/Anchorage Daily News

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ABSTRACT

This study compared two suppression systems in Quebec and Sweden: a centralized wildfire agency working with remote fires in Quebec, and a decentralized fire suppression system in Sweden, with each municipality responsible for extinguishing fires in their community. Their management approaches reflect differences in population density and land area. To understand these study areas, this study collected 25 variables, from eight national databases, that describe suppression cost, area burned, and financial efficiency for fires in 1998-2015. Descriptive analysis (histograms and frequency distributions) compared the two areas, revealing that Sweden had more fires (39,146 versus 11,211), that burned less area (0.92 ha versus 115.6 ha on average), with a lower protection cost (CAD548/ fire versus CAD10,151/ fire), and better efficiency than Quebec. Excluding fires <0.1 ha, the Swedish fires cost less to extinguish per area burned (an average of CAD839/ ha, annually, versus CAD1,860/ ha) and had a lower cost per area protected (an annual average of CAD0.04/ ha versus CAD0.52/ ha). Due to remote fire transportation needs, Quebec used more aircraft, but employed fewer people per fire. Quebec typically sent four people to the fire, while Sweden typically sent six.

To understand how firefighting agencies can suppress fires effectively and efficiently, linear models statistically evaluated the effect of suppression effort (personnel, aircraft), while controlling for climate, vegetation, remoteness, and location. Multiple lognormal models were evaluated using Akaike Information Criteria. Visual inspection of residual plots confirmed homoscedasticity, linearity, and normality assumptions. Each model used 9-16 significant variables to explain the variance and likeliness of cost ($F(23,1549)=3275$, $p<0.001$, $R^2 = 97.96\%$, AIC = 14.73), area burned ($F(43,975)=210.6$, $p<0.001$, $R^2 = 89.85\%$, AIC = 2786), and efficiency ($F(23,1549)=3866$, $p<0.001$, $R^2 = 98.26\%$, AIC = 14.73). Aircraft hours contributed more to the cost than person hours (0.59% versus 0.30% increase in cost, given a one percent increase in hours worked, $p<0.001$). However, person hours decreased area burned more than aircraft hours (-0.66% versus -0.31% change in area burned per one percent increase in hours worked, $p<0.001$). With a lower cost and larger decrease in area burned, it was more efficient (less cost per area burned) to use people than aircraft (0.30% versus 0.59% increase in cost per area burned given one percentage increase of hours worked, $p<0.001$). A larger, fulltime crew had a bigger impact on decreasing area burned than did temporary helpers (-0.41% versus -0.31% decrease in area burned given a percentage increase of people working, $p<0.01$). Therefore, the best way to suppress a fire quickly, cheaply, and efficiently is for a strong, initial attack with larger, fulltime crews.

Key Words: boreal wildfire suppression, firefighting resource, deployment, aircraft, personnel, area burned, cost, efficiency, effectiveness, response time, remoteness, Sweden, Quebec

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Table of Contents

ABSTRACT....3
ACKNOWLEDGEMENTS....5
LIST OF TABLES....7
LIST OF FIGURES....7
INTRODUCTION....9
Boreal vegetation & fire history....9
Suppression efforts to control wildfire today....10
Suppression cost, effectiveness, & efficiency....10
Objectives and scope of the present investigation....12
Hypotheses....12
METHODS....15
Study areas....15
Climate & ecology....15
People & firefighting agencies....17
Data sources....20
Fire risk information....21
Suppression information....21
Financial information....22
Statistical methods....23
RESULTS....25
Remoteness & number of fires....25
Response time....26
Resources (personnel & aircraft)....29
Area burned....32
Suppression cost....33
Financial efficiency....35
Effect on Effectiveness & Efficiency: Linear models....35
DISCUSSION....37
CONCLUSION....40
REFERENCES....42
APPENDIX....45
Appendix A: Variable list....45
Appendix B: Assumptions, calculations, and errors....50
Area burned (ha/ fire)....50
Sweden suppression costs, per fire:....54

Appendix C. Log-normal graphs..56
Appendix D. Best-fit linear models..57
Area burned (per fire) 62
Suppression cost 66
Suppression efficiency – cost per area burned...69

LIST OF TABLES

Table 1. Quebec represents a more remote area than Sweden, with less people and more land. 17
Table 2. Number of fires that occurred in Quebec's IPZ and Sweden's top five fire counties, in order of fire frequency. 18
Table 3. Time it takes firefighters to respond to a fire, as well as the total incident time. ..27
Table 4. Number of people employed to stop the fire and the hours they worked. 29
Table 5. Comparison of area burned from detection, to the start and end of the fire. 32
Table 6. Comparison of fire suppression costs, in local currency (Swedish kronor) and Canadian dollars. 34
Table 7. Comparison of fire suppression costs per area lost (area burned, per fire or year) and per area saved (the annual area not burned in the IPZ or the whole of Sweden), in local currency (Swedish kronor) and Canadian dollars. 35
Table 8. Alphabetical list of variables used in this study, their sources, and some notes. Categories include: area burned, climate, location (management region, bioclimatic zone, agency responsible), personnel (incl. aircraft), regional remoteness (forest cover & population), response time, suppression cost, and suppression efficiency. 45
Table 9. Hourly wage of fulltime firefighters in Swedish krona (SEK, kr.) and Canadian Dollar (CAD $) during the study period. 55
Table 10. Summary of linear models showing the percentage increases (+/- standard error) of area burned, suppression cost, and suppression efficiency, given a 1% increase in the independent variable. 59

LIST OF FIGURES

Figure 1. Tree species employ different strategies to survive different fire regimes, defined by differences in fire severity and return interval. Source: (Wirth, 2005)........................9
Figure 2. Location of vegetative and bioclimatic zones in Quebec. Source: (Ressources naturelles Québec, 2018)...15
Figure 3. Location of dominate forests in Sweden. Source: (Swedish University of Agricultural Sciences (SLU), 2006)...16

Figure 4. Location of the firefighting management zones in Quebec. Source: (Société de protection des forêts contre le feu (SOPFEU), 2018) 19
Figure 5. Location of highly populated areas in Quebec. Source: (Government of Canada, 2018). 20
Figure 6. Remoteness of fires in terms of regional population..25
Figure 7. Remoteness of fires in terms of percentage of forest. 26
Figure 8. Response time for firefighters to reach the fire. 28
Figure 9. Total operation time to suppress the fire 28
Figure 10. Size of fulltime crew fighting fire. 29
Figure 11 Total number of people fighting fire. 30
Figure 12 Number of part-time and temporary helpers fighting fire. 30
Figure 13. Total person-hours worked to suppress each fire. 31
Figure 14. Total flight-hours flown to suppress each fire..31
Figure 15. Area burned at the start of firefighter suppression. 33
Figure 16. Total area burned by the end of the fire 33
Figure 17. Cost to extinguish each fire 34
Figure 18. Quebec population growth from 1990-2017. 53
Figure 19. Lognormal data for each fire variable. 56
Figure 20. The importance of different variables on the area burned model results. 62
Figure 21. Area burned assumptions for the linear analysis were verified for linearity, homoscedasticity, and normality tests using residual graphs...65
Figure 22. The importance of different variables on the suppression cost model results....66
Figure 23. Suppression cost assumptions for the linear analysis were verified for linearity, homoscedasticity, and normality tests using residual graphs...68
Figure 24. The importance of different variables on the suppression-efficiency model results. 69
Figure 25. Suppression efficiency assumptions for the linear analysis were verified for linearity, homoscedasticity, and normality tests using residual graphs. 71

INTRODUCTION

Boreal vegetation & fire history

Fire is a common disturbance in boreal forests. There is a range of fire histories in the boreal forest, with species adapting to different niches. Typical boreal species include spruce (*Picea spp.)*, pine (*Pinus spp.*), birch (*Betula spp.*), and aspen (*Populus spp.*) (Natural Resources Canada (NRC) , 2018; Swedish University of Agricultural Sciences (SLU), 2017). *Picea spp.* avoid fire, appearing in places where the fire returns rarely (100+ years). *Pinus spp.* resist frequent surface fires (fires that return within 50 years). *Betula spp.* invade post-fire, where fires return every 100 years. *Populus* and *Betula spp.* endure by re-sprouting (*Figure 1*) (Pausas, et al., 2004; Lloret, et al., 2005; Wirth, 2005). These strategies may vary within the species with the local fire regime. For example, *Pinus spp.* may resist fire with thick bark, or endure with serotinous cones, to reduce fire damage to either the main stem or its seeds (Pausas, 2015; Gauthier, et al., 1996). *Pinus spp.* resisters may even embrace surface fires, by shedding long, thin needles with high surface area that dry quickly and burn readily (Pausas, et al., 2004). In contrast, the fire avoider *Picea spp.* may decrease fire risk in an area (Ohlson, et al., 2011). Deciduous species may also naturally suppress fire, as they are associated with ground fires (Feurdean, et al., 2017). In general, resisters may dominate European boreal forests, with low-intensity surface fires, while embracers and avoiders may dominate after crown-fires in North American boreal forests (Wirth, 2005). These differences may contribute to area burned by fire and the ease of wildfire suppression.

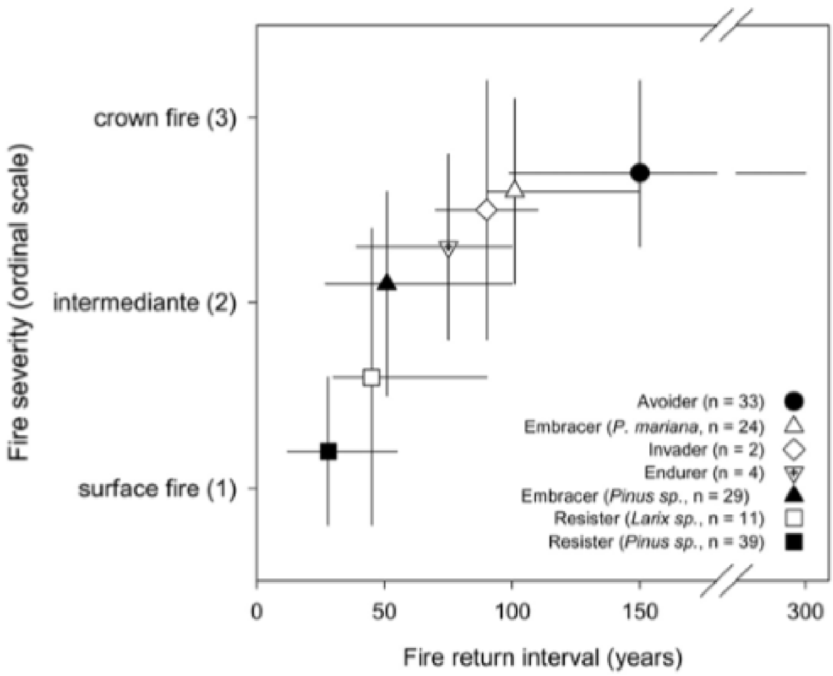

Figure 1. Tree species employ different strategies to survive different fire regimes, defined by differences in fire severity and return interval. Source: (Wirth, 2005)

Suppression efforts to control wildfire today

While boreal forests have co-evolved with fire, wildfires pose a health and safety risk to people and their property. Therefore, firefighting agencies seek to suppress fire with as little area burned as possible. Vegetative and climatic conditions can make the fire hard to suppress. This may be due to: vegetation that catches fire easily**,** a locality, season, or day that is prone to drought and high temperatures**,** or a day with worse fire weather conditions (Stocks, et al., 1989; Tedim, et al., 2015; Ganteaume, et al., 2013; Natural Resources Canada (NRC) , 2018).

Remoteness and population density also impact wildfires. Fires typically start near a road or developed area (Ganteaume, et al., 2013). These fires are located closer to people, who will detect and report them quickly. In contrast, remote fires may be detected at larger sizes if they occur in a sparsely populated area, far from the firefighting agency. While some firefighting agencies actively search for remote fires via aircraft or lookout towers (Pyne, 2006), many rely on passive detection sections where the citizens must notice and report fires. In less populated areas, passive detection systems are weaker. Furthermore, larger areas to protect may make it more difficult for the agency to respond before the fire is large, as the fire has a higher chance of being further away. This is especially true if the protected area is large and remote, with few roads. The longer it takes an agency to respond to a fire, the larger and more uncontrollable the fire. This may increase suppression cost.

While remoteness, regional population, vegetation, and climatic conditions may affect the ability to suppress the fire, the firefighting agency cannot control these variables. Hence, these values are included as control variables in this study, not as indicators of the agency's success. The firefighting agency can control the resources fighting the fire and the total suppression effort (personnel and aircraft hours dedicated to the fire). Having arrived at the fire, successful suppression depends on the resources deployed. If too few people respond to the fire, it may be difficult for them to extinguish it, however too many people may needlessly increase the cost. Too few people may increase the hours worked, the area burned, and the overall compensation to the firefighters, offsetting the gain saved by sending fewer people. Difficult fires may require more resources and costly airplane support. Aircraft usage may be more effective at stopping the fire, leading to a faster response, a more controllable fire for the crew, less area burned, and shorter operation times (Pyne, 2006). This may or may not offset the cost of using them, as aircraft cost more per hour than people do. Finding the balance between fire risk and resources used is key to suppressing fires efficiently.

Suppression cost, effectiveness, & efficiency

Of great concern to firefighting agencies is how to suppress fires efficiently. *Financially efficient* fire suppression extinguishes fires for as little money as possible, given the size of the fire; a smaller cost to reduce a hectare burned is more efficient than a larger cost.

$$Suppression\ Efficiency = \frac{Cost\ to\ extinguish\ fire}{Area\ burned}$$

Financially effective fire suppression seeks to minimize the financial cost per fire. Sending one firefighter to suppress a fire is cheaper than sending two, but the fire may be too large for that firefighter to suppress by themselves. The financial cost may be small, but the area burned large.

Effective fire suppression will suppress a fire when it is small – before much area has burned. The area burned at the start of the fire reflects the effectiveness of the fire detection and response systems – how quickly the firefighters located and reached the fire. The area burned at the end of the fire represents the effectiveness of the entire suppression system: the detection, response, and attack to extinguish the fire. Dedicating many resources (people and aircraft) to a fire may quickly suppress a fire. However, these resources may be expensive. Effectively suppressing a fire for a high cost leads to a poor efficiency. Firefighting agencies want to suppress the fire quickly, for as little cost as possible.

Firefighting costs can be divided into the variable suppression costs and the pre-suppression, or fixed costs (Stocks & Martell, 2016). The annual budget describes the *total cost* necessary to operate the firefighting agency and respond to all emergencies.

$$\begin{aligned} Annual\ Budget &= Total\ Cost \\ &= \sum_{Emergencies} Personnel + Equipment + Facilities \ldots \end{aligned}$$

The *suppression costs* describe the cost incurred by fighting the fire, and include the cost of people, aircraft, and other equipment used to suppress the fire. The *fixed costs* describe the costs to prepare for the fire season and include the costs to purchase and maintain the firehouse, permanent staff, and equipment. Long-term, strategic decisions may influence these costs. For example, the decision to invest in expensive (but more effective) equipment can increase the annual, fixed costs, but the cost to suppress each fire will decrease as the crew can more quickly extinguish the fire. Another example is to invest in more firefighting bases that are located close to fire-prone areas. While expensive to maintain, these fixed costs may decrease the variable costs with faster response times.

Objectives and scope of the present investigation

This study seeks to compare the fire suppression efforts of Quebec and Sweden during the period of 1998-2015. Quebec and Sweden represent two wildfire suppression systems operating in boreal forests, but with different approaches. By comparing these fire suppression systems, this study seeks to understand the common conditions that affect fire suppression, as well as identify differences that may impact suppression efficiency. While fixed costs and long-term, strategic decisions may affect the suppression effort, this study will focus on the variable suppression costs. Suppression costs are more sensitive to changes in fire behavior and can better explain how the costs vary across fires. Variable costs are more comparable across different regions, with different fire suppression systems and associated fixed costs. Questions to be answered include:

Part I: Descriptive analysis

- **How do Quebec and Sweden compare in their suppression response?** (e.g., response time, area burned, resources used to suppress the fire, suppression cost, and efficiency)

Part II: Statistical analysis

- Considering climatic conditions, vegetation, population density/ remoteness, and suppression effort, **what impacts suppression cost, area burned, and suppression efficiency?**
- Since the agency can only control their suppression effort (number of people; personnel, aircraft hours worked), **what can the agency do to decrease the cost, reduce area burned, and improve efficiency?** When deploying resources, were people or aircraft more affordable, effective, or efficient? Was there a difference between fulltime and part-time crew? When climatic conditions, vegetation, remoteness, and suppression effort are controlled, was one system more efficient than the other was?

Hypotheses

In Quebec (a more remote area):

1. **Remoteness & number of fires.** Quebec represents a more remote area than Sweden, with a lower population density and more forest cover. There will be fewer fires, with fewer people to start them.

2. **Response Time.** The firefighters will take longer to respond to a fire, because the fires are further away. The total operation time will be longer, with a more severe fire to extinguish upon arrival.
3. **Resources used** (number of people & aircraft used). More resources will be needed to extinguish the fire, since it is larger and more difficult to reach.
4. **Resources – hours worked.** A larger suppression effort (hours worked) will be needed for the more severe fire.
5. **Effectiveness - area burned.** Fires will be larger upon arrival of the firefighters and more area will be burned. This is less effective.
6. **Financial effectiveness - suppression cost.** Remote fires will require more resources (more people or aircrafts) to decrease the area burned. This will be more expensive (less financially effective).
7. **Financial efficiency (overall resources).** Using more resources (more people or aircraft) will decrease the area burned more effectively. An expensive suppression effort will be more efficient with larger, remote fires (more area burned to justify the cost).
8. **Resource usage - people versus aircraft.** Using more aircraft as compared to people may be more effective at reducing area burned, as aircraft can reach remote areas faster than trucks and drop more water. Aircraft may cost more than people, but this may be efficient.

Conversely, in Sweden (a more densely populated area):

1. **Remoteness & number of fires.** Sweden represents a more developed area than Quebec, with a higher population density and less forest cover. There will be more fires, with more people to start them.
2. **Response Time.** The firefighters will respond faster, assuming the road network is better, and the fires are closer. The total operation time will be less, with a less severe fire to extinguish upon arrival.
3. **Resources used** (number of people & aircraft used). Less personnel and aircraft will be needed to extinguish the fire, since it is smaller and closer.
4. **Resources – hours worked.** A smaller suppression effort (hours worked) will be needed for the less severe fire.
5. **Effectiveness - area burned.** The fires will be smaller upon arrival of the firefighters and less area will be burned.
6. **Financial effectiveness - suppression cost.** The suppression will be more financially effective (less resources needed, less cost).
7. **Financial efficiency.** Using more resources (more people or aircrafts) will decrease the area burned more effectively (same as in a remote area); however, this higher cost will not be efficient. Efficiency will improve if fewer resources (people and aircraft) control the smaller fire (less cost per area burned).
8. **Resource usage - people versus aircraft.** Using more aircraft as compared to people may be more effective at reducing area burned, as aircraft can arrive

faster and drop more water; however, the higher cost of aircraft will not be efficient.

Overall, the costs are expected to increase with suppression effort. The area burned will increase with difficulty to extinguish the fire (more remote fires, larger fires on arrival, or poor fire weather – dry, hot, windy days), but should decrease with the use of more resources (personnel, aircraft). More resources to suppress the fire should decrease the area that could have burned, had there been no suppression effort at all. Estimating the benefit (the area that could have burned but did not) for each fire is beyond the scope of this study. Hence, efficiency is described as the lowest cost per area burned. However, the annual benefit of the cost per area protected (the management area that did not burn that year) will be briefly mentioned. The most efficient system is that which extinguishes the fire as cheaply as possible, using the right resources for the job.

METHODS

Study areas

This study compares the wildfire suppression systems in Quebec and Sweden. These areas share broad climatic and ecological pasts as boreal forests, but differ in their population density, cause of fires, and fire suppression systems. A discussion of differences between and within each study area follows.

Climate & ecology

Most forests in Quebec and Sweden are boreal. In Canada, 95.4% of the volume in the boreal shield consists of six species: spruce (51.4% *Picea spp.)*, poplar (e.g., aspen, 15.3% *Populus spp.*), pine (10.7% *Pinus spp.*), birch (8.4% *Betula spp.*), maple (5.2% *Acer spp.*), and fir (4.5% *Abies spp.*) (Canada's National Forest Inventory (NFI), 2018). Quebec boreal forests are mostly spruce dominated, with a birch and fir transition into maple dominated hardwood forests in the south (*Figure 2*).

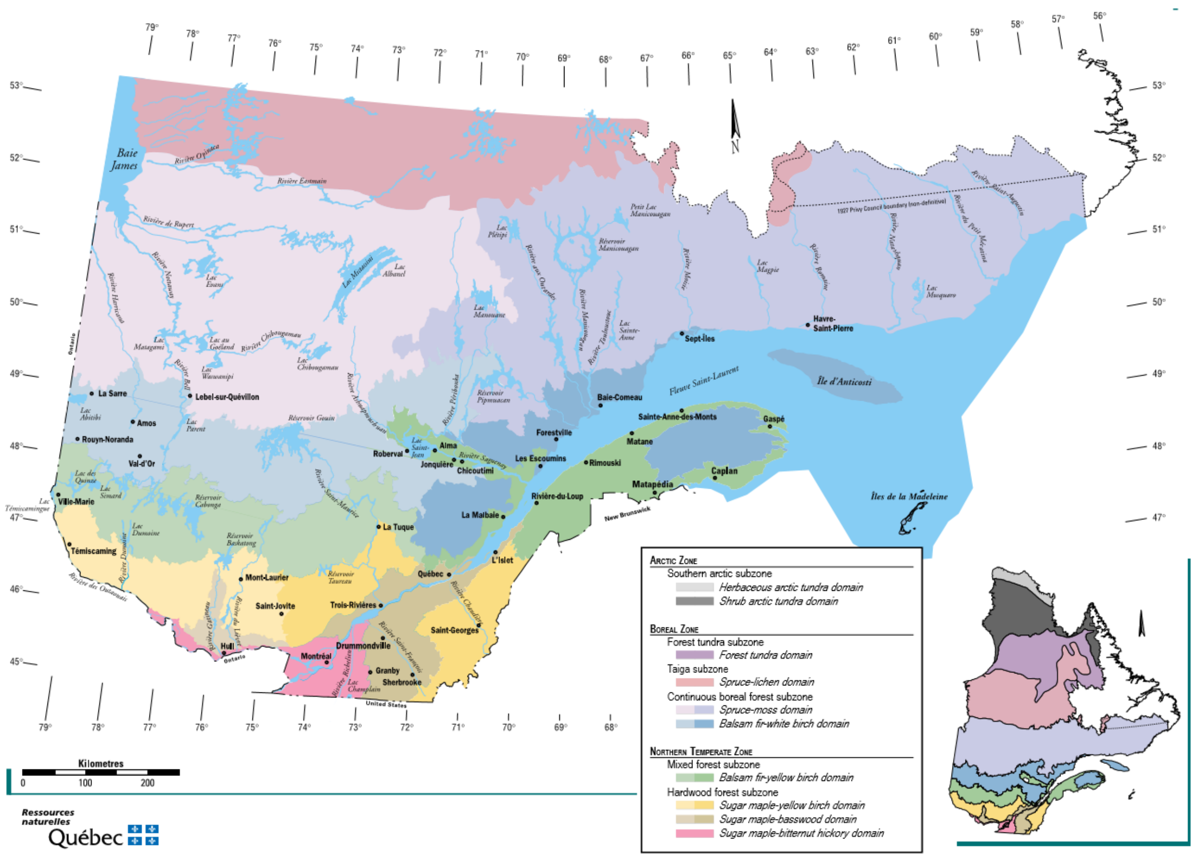

Figure 2. Location of vegetative and bioclimatic zones in Quebec.
Source: (Ressources naturelles Québec, 2018)

Spruce and pine dominate Sweden's forests, with broadleaves being more common in the south (*Figure 3*). In Sweden, 95% of the standing volume consists of five species: spruce (41% *Picea spp.*), pine (40% *Pinus spp.)*, birch (12% *Betula spp.)* oak (1% *Quercus spp.*), and beech (1% *Fagus spp.*) (Swedish University of Agricultural Sciences (SLU), 2017). Spruce, pine, and birch are in the top four species in both areas, with aspen (similar in fire ecology to birch) common in Quebec. These species have adapted to their local fire histories, and their different flammability may influence the ease of fire suppression.

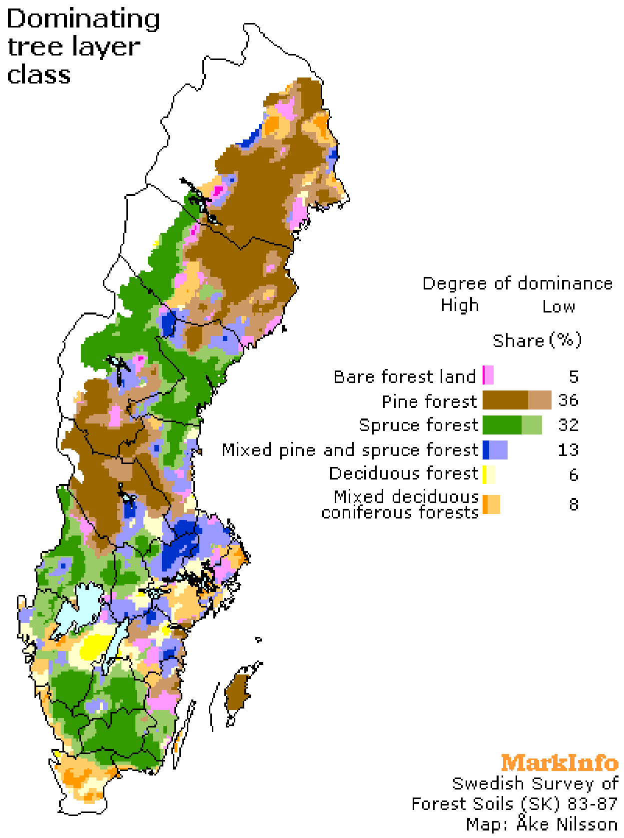

Figure 3. Location of dominate forests in Sweden.
Source: (Swedish University of Agricultural Sciences (SLU), 2006)

Historically, fire is common in boreal ecosystems. In Canada, fire may return to an area every 35-120 years (Natural Resources Canada (NRC) , 2018). Frequently these fires are small surface or ground fires, but there can be large, stand-replacing crown fires. While 97% of Canadian fires burn less than 200 hectares (Stocks, et al., 2002), these large fires account for 92% of the total area burned (Natural Resources Canada (NRC) , 2018; Krezek-Hanes, et al., 2011). In Sweden, the fire regime has changed over time. Historically, large (>1000 ha), rare fires burned 90% of the area (1350-1650); then humans increased the frequency of small fires (1650-1860), so that 55% of the area burned was due to fires >1000 hectares; finally, all fires were strongly suppressed (1860-today) (Niklasson

& Granström, 2000). While Quebec still has large crown fires, frequent ground fires are more common in Sweden today.

Typical fire seasons run in the summer, from April – October (Natural Resources Canada (NRC) , 2018), during the hot, dry season. In both countries, the mean annual temperature and growing season are higher in the south than the north (Natural Resources Canada (NRC) , 2018; Swedish University of Agricultural Sciences (SLU), 2006). Climatically, this may increase the risk for fire to occur in the south; however, this also affects the vegetation present. In both areas, spruce, pine, and birch are common, with more deciduous species in the south *(Figure 2, Figure 3*). Deciduous species may be less prone to severe fires and offset the climatic risk.

In Sweden, the annual precipitation and humidity during the vegetative period are higher on the west coast (in the south) than the east coast (Swedish University of Agricultural Sciences (SLU), 2006), making the east coast more climatically at risk of fire. In Quebec, the east coast gets more rain than the more continental part in the west (Natural Resources Canada (NRC) , 2018). These different vegetative and climatic zones will be included as a control variable in this study.

People & firefighting agencies

Quebec and Sweden have evolved different firefighting systems as a response to different human influence. Population density is higher in Sweden, with a third of the land and a fifth more people than in Quebec (Government of Canada, 2018; Statistiska centralbyrån (SCB), 2017) **(***Table 1***)**. Hence, Sweden may have a denser road network and more human-caused fires. Before 1860, when fire suppression became common, the frequency of small, human-caused fires was 11.7 times higher than present-day lightning ignitions (Niklasson & Granström, 2000).

Table 1. Quebec represents a more remote area than Sweden, with less people and more land, even in the IPZ.

Region	Population density (people/ ha of land)	Average Population 1998-2015	Forest land (kha) 2014	Total land (kha) 2014	% Forest
All of Sweden	0.226	9,226 K	30,651	40,816	72%
All of Québec	0.046	7,702 K	76,100	166,700	46%
Québec's IPZ	0.148	7,702 K	46,720	51,913	90%

In contrast, Quebec is more remote, with a lower population density. From 2008-2017, 23% of the fires were lightning ignited (3.3 times as many human fires as lightning ignited), causing 88% of the total area burned (Société de protection des forêts contre le feu (SOPFEU), 2018). These remote fires may be detected later, be more difficult to reach, and occur in multiple locations simultaneously, challenging the agency's resources. To detect, monitor, and suppress these remote fires before they are large, SOPFEU regularly uses airplanes; Sweden, however, rarely uses planes. In more populated areas, they both rely on the public to detect and report fires. In less populated areas, this detection system is weaker.

Table 2. Number of fires that occurred in Quebec's IPZ and Sweden's top five fire counties, in order of fire frequency.

Region	Number of fires	Percentage of all fires (SWE+Q)	Fires/ person	Fires/ha of forest	Population density (people/ ha of land)	Population average (people) 1998-2015	Forest land (kha) 2014	Total land (kha) 2014	% Forest
All of Sweden	39,146	77.74%	0.004	0.0013	0.226	9,226 K	30,651	40,816	72%
Québec IPZ SOPFEU 1st Municipalities	11,211 6,588 4,623	22.26% 13.08% 9.18%	0.001	0.0002	0.148	7,702 K	46,720	51,913	90%
Top 5 counties in Sweden with the most fires									
Stockholm	10,298	20.45%	0.005	0.0265	2.910	1,959 K	388	673	58%
Västra Götaland	6,509	12.93%	0.004	0.0044	0.659	1,548 K	1,496	2,350	64%
Södermanland	1,917	3.81%	0.007	0.0048	0.426	266 K	401	624	64%
Östergötland	1,623	3.22%	0.004	0.0023	0.408	422 K	694	1,036	67%
Gävleborg	1,574	3.13%	0.006	0.0010	0.147	278 K	1,652	1,883	88%

In Sweden, the local emergency service handles wildfires, with 290 municipalities tasked to suppress fire. For financial efficiency, some of these municipalities have combined into joint-agencies, where the communities share firefighting resources: in 2015, there were 167 total agencies, whereas 2005 had 203 (Statistiska centralbyrån (SCB), 2017). While all agencies require personnel, some Swedish municipalities lack personnel costs – these cities may pay their neighbor to suppress fires, or they may be volunteer run. Furthermore, in Sweden, there is no dedicated wildfire agency, so the municipal emergency service budgets include forest fires, building fires, and non-fire emergencies like traffic accidents. Joint-agencies rarely extend across county lines.

<u>Sweden's Emergency Response Structure</u>

- Counties – 21 *Län* – agreements between agencies operate at this level
- Agencies – 203 to 167 (2005-2015) (Statistiska centralbyrån (SCB), 2017)
- Municipalities – 290 *Kommun* – each with their own emergency budget

Quebec used to have multiple wildfire agencies but reorganized in 1994 to optimize resources and reduce costs (Société de protection des forêts contre le feu (SOPFEU), 2018). Now there is one wildfire agency, SOPFEU (in French, *Société de protection des* *forêts contre le feu*, or the “Society for the protection of forests against fire,” in English). SOPFEU manages fire in two zones: an *Intensive Protection Zone* (IPZ), where all fires threaten communities and must be suppressed, and a *Northern Protection Zone*, where remote fires are monitored and suppressed only if they approach a community (Société de protection des forêts contre le feu (SOPFEU), 2018). In Figure 4**,** the green region represents the IPZ, where most people live, and fires are always suppressed. The white region represents the Northern Protection Zone, where all fires are monitored, but not necessarily suppressed. The dots in the green area represent firefighting bases. Rather than 290 municipalities, there is one main office (in Quebec City), four main bases (in Baie-Comeau, Roberval, Maniwaki and Val-d'Or), and 24 secondary and support bases (29 total) (Société de protection des forêts contre le feu (SOPFEU), 2018).

Figure 4. Location of the firefighting management zones in Quebec.
Source: (Société de protection des forêts contre le feu (SOPFEU), 2018)

These differences in protection reflect the province’s population density. Quebec has twice as much forest as Sweden, and less people (Government of Canada, 2018; Statistiska centralbyrån (SCB), 2017) (*Table 1*). Since most people live in the south (*Figure 5*), it makes sense to protect that area more than the north. For these reasons, Quebec created an IPZ where all fires are suppressed. Even assuming the entire population of Quebec lives in the IPZ, the IPZ is more remote than Sweden (*Table 1*). For comparability with Sweden’s suppression policy, this project focused on Quebec’s IPZ.

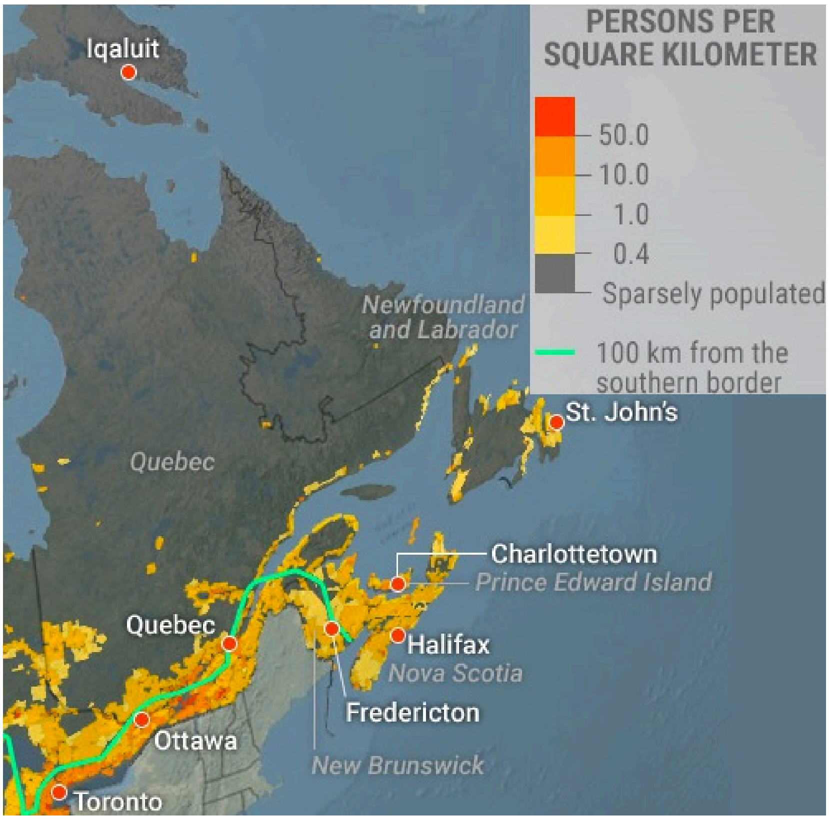

Figure 5. Location of highly populated areas in Quebec.
Source: (Government of Canada, 2018).

Note that forest fires that are small and occur near a municipality may be suppressed by the local firefighters and reimbursed by SOPFEU. Fires for which the municipality was the first responder will be included in this study as a separate agency from SOPFEU, since these fires differ in remoteness from SOPFEU's fires.

Data sources

Data came from a variety of national databases. In Quebec, Statistics Canada provided population data (Government of Canada, 2018), Natural Resources Quebec provided bioclimatic data (Ressources naturelles Québec, 2018), and SOPFEU provided all fire-related information (Société de protection des forêts contre le feu (SOPFEU), 2018). In Sweden, the Swedish Civil Services, MSB (in Swedish, *Myndigheten för samhällsskydd och beredskap*), provided the fire incident report database, with variables describing the fire's size and the agencies' response time and hours worked (Myndigheten för samhällsskydd och beredskap (MSB), 2017). The Swedish Statistics Agency, SCB (in Swedish, *Statistiska centralbyrån*), provided the financial information about firefighting wages and population data (Statistiska centralbyrån (SCB), 2017). Sweden's National Forest Inventory provided information about the forest area and species in each county

(Swedish University of Agricultural Sciences (SLU), 2017). By combining these databases, over 50 variables were obtained for Sweden, with 25 of them comparable with Quebec (see Appendix C: Variable list and Appendix D: Assumptions, calculations, and errors). A short-list of key variables was identified and analyzed, consisting of data describing the fire risk, the agency's response, and the costs to extinguish the fire.

Fire risk information

These data describe the climatic, vegetative, and regional risk of fire:

Bioclimatic zone – describes the vegetation and local weather conditions. In Quebec, this consists of six zones, divided into east and west (Ressources naturelles Québec, 2018). In Sweden, this consists of three zones: boreal (in the north) or hemi-boreal (in the south), with the hemi-boreal divided into east and west (reflecting differences in precipitation) (Swedish University of Agricultural Sciences (SLU), 2006).

Climatic risk – describes the climatic risk of fire activity on the day the fire starts; these variables account for seasonal differences and changes from day to day:

Fire weather index (FWI) – describes the overall fire risk: how much fuel may burn (Buildup Index) and how fast the fire will spread (Initial Spread Index, ISI). It is based on fuel moisture (relative humidity, temperature, rain), drought (temperature and rain in the last 24 hours), and wind (Natural Resources Canada (NRC) , 2018; Stocks, et al., 1989).

Initial Spread Index (ISI) – describes the risk of fire spreading, a subset of the FWI based on fuel moisture (ease of ignition) and wind (NRC, 2018).

Wind speed – contributes to fire spreading quickly, a subset of the ISI and FWI.

Population density – describes the risk of fire starting due to people. Increases over time.

Size of forest and land area – describes how much of the landscape is forested and protected in the management region (IPZ or Swedish county). Assumed constant over time.

Suppression information

These data are key variables to describe the firefighting agency's suppression effort:

Area burned (ha/ fire) **–** total area burned by the end of the fire
Area burned at start of fire (ha/ fire) – area burned when the attack begins

Incident time (hours/ fire) – time from SOS report to fire declared out (Quebec) or end of the attack (Sweden). Some Swedish operations end while embers still glow, so this is not 100% comparable.

Response time (hours/ fire) – time from SOS report to start of attack

Total personnel working the fire – both regular, fulltime employees, plus temporary/ seasonal employees (Quebec), contractors, volunteers (Sweden), military (Sweden), and any other external resources.

Person and flight hours spent working (hours/ fire) – from notification to end of attack. Aircraft activities include transportation of personnel, aerial supervision to coordinate the attack, and active suppression (dropping water or retardant on the fire). Personnel activities include planning and overseeing the attack, active suppression, and building fire breaks to contain the fire.

Financial information

These data are key variables to financially describe the agency's suppression effort:

Variable suppression cost – financially describes the effort to extinguish each fire

Inflation – controlled for by increases in the fulltime firefighter wage

For a more similar comparison between the two areas, this study focused on the **variable suppression costs**, representing the suppression effort for each fire. SOPFEU provided an estimate for these values, with the disclaimer that they include some pre-suppression costs and may not represent the actual costs per fire. In Sweden, these costs were calculated for each fire, using this equation:

$$Suppression\ Costs = (Total\ person\ hours * \ wage) + (Flight\ hours * rent)$$

For simplicity, the equipment cost was assumed to be negligible. This may not be true, as a Swedish report suggested that equipment costs may double personnel costs, with larger fires incurring more costs (Bratt & Sandahl, 1996). However, there was no easy way to estimate these values for both study areas. Additionally, there was assumed to be no overtime pay and no difference between fulltime and part-time wages (including military and volunteer support). For comparison between countries, the Swedish suppression costs were calculated once in local currency (Swedish krona, kr.) and once using Quebec's financial data (in Canadian dollar, CAD). Using the same currency and hourly costs to compare the two areas allows for some control over differences in market prices and costs of living. Note that no financial data were corrected for inflation. To account for inflation, the model includes the firefighting wage as a control variable. Additional information is in Appendix D: Assumptions, calculations, and errors.

Statistical methods

To assess how fires in the two countries compared, their key variables were described with basic statistics (histogram frequency plots, quartile distributions), and any key differences noted. R (R Core Team, 2018) evaluated the basic statistics, and the R library, *ggplot2*, (Wickham, 2009), created the histograms comparing Quebec and Sweden. As all firefighting agencies are striving to minimize these variables and their costs, the data were then log-transformed to get a normal distribution (Appendix E. Log-normal graphs), excluding zero values. As fires less than 0.1 hectare are reported as zero, this analysis excluded them.

Statistical linear analysis used the lognormal data to evaluate the influence of each variable on suppression costs, area burned, and suppression efficiencies. Using data from both study areas, a global linear model included all variables in R:

Global Linear Model:

$$\log (Y) \sim \log (X_1) + \log (X_2) + \ldots \log (X_n) + \text{Country} + \sum \log(\text{control variable}_i)$$

$\mathbf{Y_1}$ = area burned, $\mathbf{Y_2}$ = suppression cost, $\mathbf{Y_3}$ = cost per area burned
X = key variables of interest, representing the suppression effort:

- Area burned – at the start and end of the attack
- Fire flight hours (total)
- Number of people (Full-time, part-time, and total)
- Person hours worked (Full-time, part-time, and total)
- Response time – how long it takes to arrive at the fire and extinguish it

Country = Quebec or Sweden, subdivided into region (21 counties or IPZ), and agency (291 municipalities, plus SOPFEU) – This is a categorical variable, it was not log transformed.

Control variables = variables that may affect the cost and area burned, but are not controllable by firefighting agencies:

- Bioclimatic zone (local vegetation and weather) – categorical, not log-transformed
- Climatic fire risk (Fire Weather Index (FWI), Initial Spread Index (ISI), Wind speed)
- Inflation (represented by increases in the full-time wage)
- Regional factors (population, forest, and land to protect)

(See Appendix F. Best-fit linear models, for more details).

The R library *glmulti* (Calcagno, 2013), used this global model to create and analyze multiple models using Akaike Information Criteria (AIC). Glmulti allows for automated model selection for the most likely model (lowest AIC); variables that are not significant and do not help explain the variance are excluded from the best-fitting model (Calcagno & de Mazancourt, 2010). Due to the number of variables in this study, the genetic algorithm method was used, and interactions between variables were excluded. This decreased computational time with a bias for selecting the best model, but not all possible models were evaluated. As many of these variables explain similar variance, the top six models were reviewed, and those variables that did not contribute significantly to explain the variance (R^2 changed <0.01%) nor the overall likeliness of the model (AIC within 2) were excluded from the best model. (For an example of how to use glmulti for this type of analysis, see (Hartman, 2013)). Visual inspection of residual plots confirmed homoscedasticity, linearity, and normality assumptions for the best model. (For an example on how to verify assumptions and interpret linear models in R, see (Winter, 2013)).

With log-log linear models (lognormal independent and dependent variables), the linear relationship between the variables is a ratio or percentage increase (Benoit, 2011; Yang, 2012; UCLA: Statistical Consulting Group, 2018)). For example, a percentage increase in the independent variable may increase the dependent variables by 25%, or 1.25 times (i.e., 100% +25%) the independent variable. For larger values, the gain between values increases. Conversely, if the value is negative, a percentage increase in the independent variables causes the dependent variables to decrease at that percentage; a value of -25% would be the same as multiplying by 0.75 (i.e., 100% - 25%) the independent variable. A starting value of 16 would decrease 25% to 12 (16 * 0.75 = 16 – 4 = 12); 12 would decrease 25% to 9 (12 * 0.75 = 12 – 3 = 9). For smaller values, the difference lost decreases. A smaller (ideally negative) value is preferred to decrease the cost, area burned, and efficiency. These values are in the results section.

RESULTS

Descriptive histograms show the difference between Quebec and Sweden in terms of key variables describing their suppression effort (response time, area burned, personnel, hours worked, and suppression cost, *Figures 6 - 17*). For readability, graphs were zoomed in, excluding the larger values. Quebec is more remote (fewer people, more forest) than most of Sweden's counties, although a few Swedish fires occurred under similar conditions (*Figure 6*, *Figure 7*). Even when using aircraft instead of trucks to transport equipment and crews, Quebec's fires took longer to reach (*Figure 8*) and extinguish (*Figure 9*). (The sinusoidal wave for total incident time in Quebec reflects the fact that SOPFEU does not work at night.) Quebec employed fewer people per fire than Sweden did, with the main difference being less fulltime crew deployed (*Figures 10 - 12*). Yet Quebec's crew worked more hours (*Figure 13*), especially their aircraft (*Figure 14*)! With longer response times, Quebec's fires were larger upon arrival (*Figure 15*). With larger initial fires and fewer firefighters, more area burned (*Figure 16*). With more aircraft and fewer people working longer hours, Quebec's costs were larger (*Figure 17*). These variables and more detailed differences between them will be noted next.

Remoteness & number of fires

Quebec represented a more remote area, with fewer people per area (0.148 versus 0.226 people/ ha), and more forest cover (90% versus 72%) than Sweden (*Table 1*). However, some counties in Sweden had similar population densities and forest cover (*Table 2*, *Figure 6*, *Figure 7*). Reflecting their lower population, Quebec had fewer fires than Sweden (11,211 versus 39,146; *Table 2*). Surprisingly, there were fewer fires per person in Quebec (0.001 versus 0.004 fires/ person), perhaps reflecting greater awareness to human-caused fires. Three and a half times as many fires occurred in Sweden than in Quebec, with four times as many fires per person and six times as many fires per hectare of forest, although this varied within Sweden. Hence, local differences in remoteness may have a larger effect on fire suppression than differences between fire-fighting agencies.

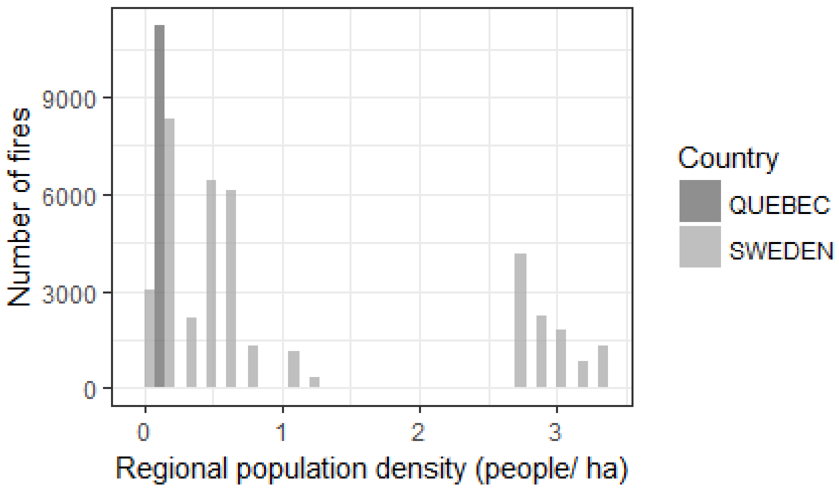

Figure 6. Remoteness of fires in terms of regional population.

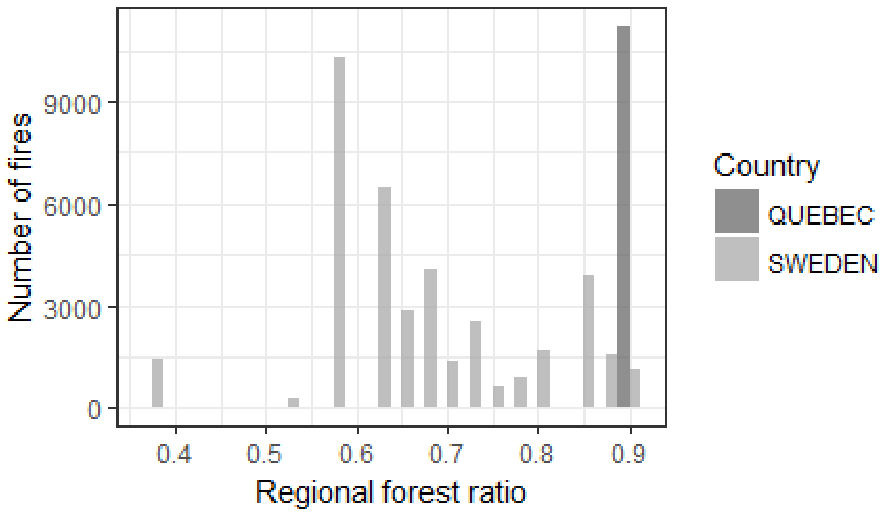

Figure 7. Number of fires and forest ratio (forest area/total land area).

Comparing agencies within each study area, SOPFEU, Stockholm County, and Västra Götaland suppressed the most fires (*Table 2*). Within these counties, the Swedish municipalities that extinguished the most fires were Göteborg (2,986 fires in Västra Götaland) and Stockholm (2,909 fires in Stockholm county). These cities are the top two most populated cities in Sweden, with the most people living near the capital, Stockholm (Statistiska centralbyrån (SCB), 2017). These fires were in more urban areas than SOPFEU's protection zone. While more frequent, less remote fires may be easier to suppress.

Note that differences between the two counties in Sweden may also reflect climatic differences, as the west coast of Sweden (Västra Götaland) experiences more rain than the east coast (Stockholm) (Swedish University of Agricultural Sciences (SLU), 2006).

Response time

In Quebec, it takes an hour to respond to most fires (75%); half of the fires are declared out within a day, and 75% are extinguished within two days (*Table 3*). Due to safety reasons and a lower fire risk at night, fires reported at night are attacked the next morning. When SOPFEU does not have enough resources to address a lower priority fire, it may be days before they can respond. Large, remote fires under bad fire weather conditions may take weeks to extinguish.

In Sweden, half the fires can be reached in 15 minutes, with 75% reached within 25 minutes; most operations last less than an hour, with 75% of the operations ending within two hours (*Table 3*). MSB could not recall any emergency service attacking a fire after three hours had past, nor did they remember any operations lasting over a month (31 days). However, some fires are left for the property owner to monitor and mop-up once under control. These fires may restart (2.5% of all fires from 2006-2015) after the initial operation has ended. These fires are often reported as a new fire incident, although it is possible that an agency records them as a continuation of the initial fire. For this study, the large values reported for response and incident times (<0.25% each) were believed to be typos. They were replaced with average times that reflect the agency's performance that year.

Table 3. Time it takes firefighters to respond to a fire, as well as the total incident time.

	Quebec's IPZ		Sweden	
Value	Response time	Incident time	Response time	Incident time
Min	0	0	0	0
1st Qu.	15 min.	3.75 hr.	10 min.	30 min.
Median	30 min.	21.25 hr. (<1 day)	15 min.	1 hr.
Mean	3 hr.	47.75 hr.(2 day)	20 min.*	2.5 hr.*
3rd Qu.	1 hr.	46.75 hr.(<2 day)	25 min.	2 hr.
Max	458 hr. (19 day)	2493 hr.(15 wk.)	5 hr.*	746 hr.*(31 day)

On average, fires in Quebec are attacked 2.5 hours later than in Sweden, and the operation lasts almost 2 days longer (*Table 3*, *Figure 8*, *Figure 9*). While this difference between remote and developed areas was expected, it is not entirely comparable. The operation time in Quebec ensures that no embers are glowing when the firefighters leave, so the fire cannot restart. In Sweden, the fire will always be controlled and suppressed so that there are no flames, but the organic layer may retain heat and smolder for days afterwards. The Swedish landowner assumes responsibility to report if the fire restarts. It was not possible to estimate how long it would take Sweden to ensure the fire cannot restart. While no additional area burns during this period, differences in suppression standards can contribute to differences in the cost.

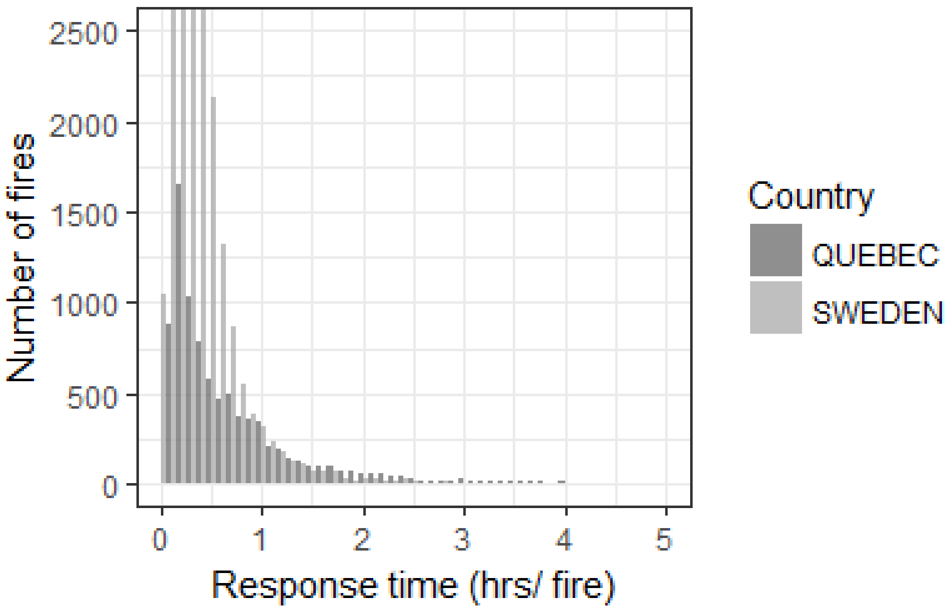

Figure 8. Response time for firefighters to reach the fire.

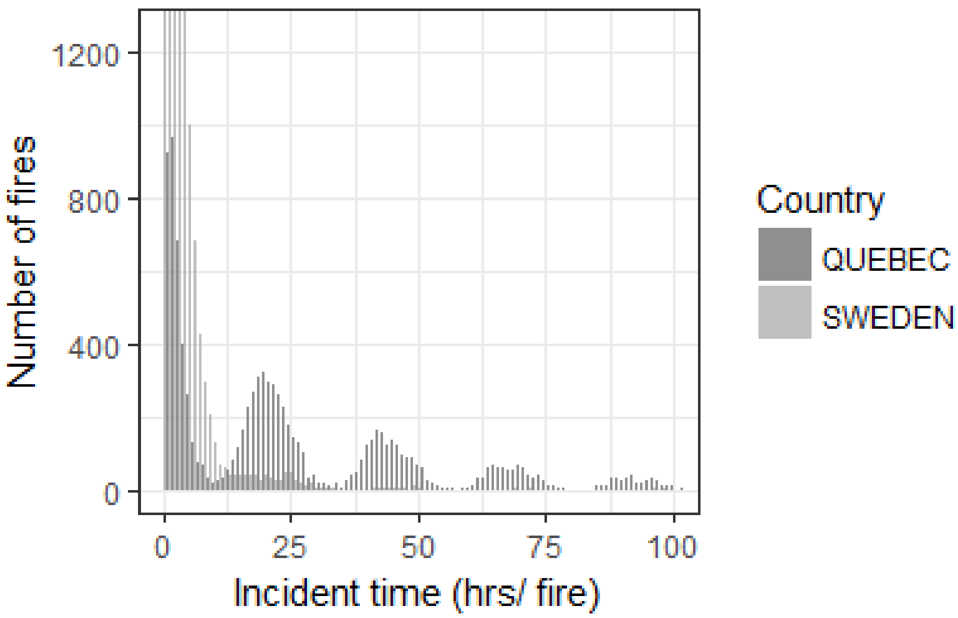

Figure 9. Total operation time to suppress the fire

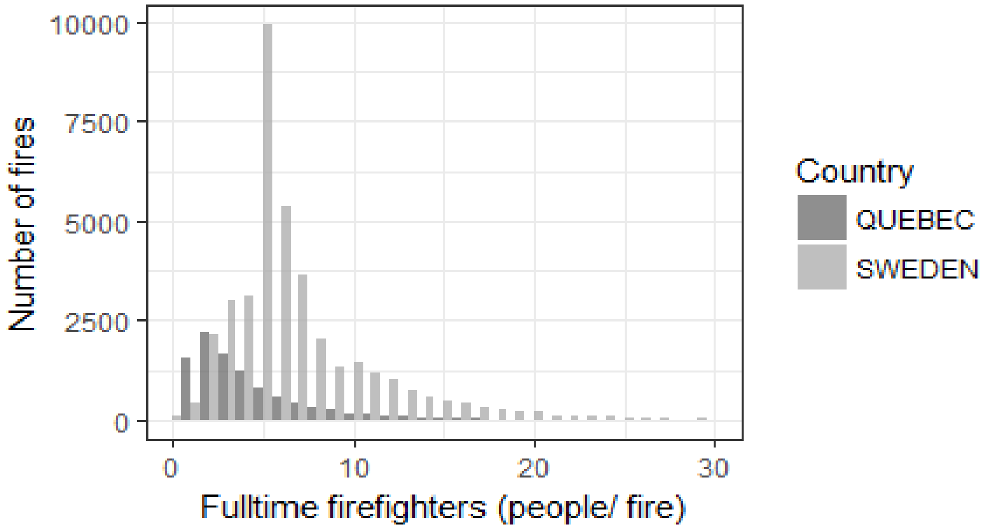

Figure 10. Size of fulltime crew fighting fire.

Resources (personnel & aircraft)

For both study areas, most fires (75%) were suppressed by eight or fewer people, working 23 hours between them (*Figure 11)* Regular crew members (fulltime seasonal or permanent employees) primarily suppress the average fire: 93% of the crew was fulltime in Quebec, 99% in Sweden. Part-time firefighters, other firefighting agencies, temporary contractors (in Quebec), the military (in Sweden), and citizen volunteers (in Sweden) were only used in the most extreme cases (*Figure 12)*. Quebec used 1.5 more part-time people on average, but not as many people for the worst fire (*Table 4*).

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Table 4. Number of people employed to stop the fire and the hours they worked.

	Quebec's IPZ					Sweden				
Value	FT crew	PT crew	Total crew	Person hours	Flight hours	FT crew	PT crew	Total crew	Person hours	Flight hours
Min	0	0	1	0.25	0	0	0	0	0	0
1st Qu.	2	0	2	13	2	5	0	5	2.75	0
Median	3	0	4	30	4.5	6	0	6	5.75	0
Mean	5	1.5	6.5	237.25	17.25	7.5	0	7.5	18	0.25
3rd Qu.	6	0	6	80.5	9.75	8	0	8	14.5	0
Max	114	370	484	92,174	3,478	656	434	656	11,072.5	2,000

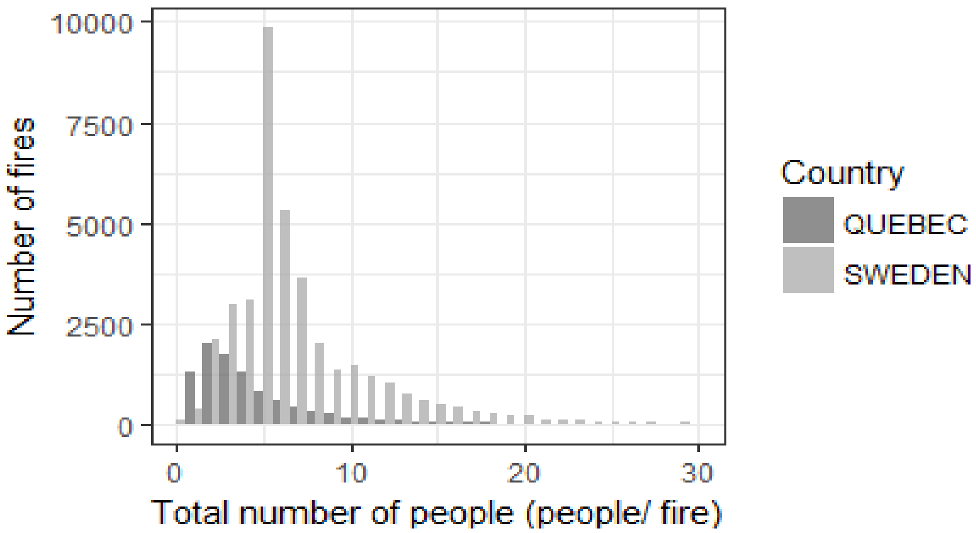

Figure 11 Total number of people fighting fire.

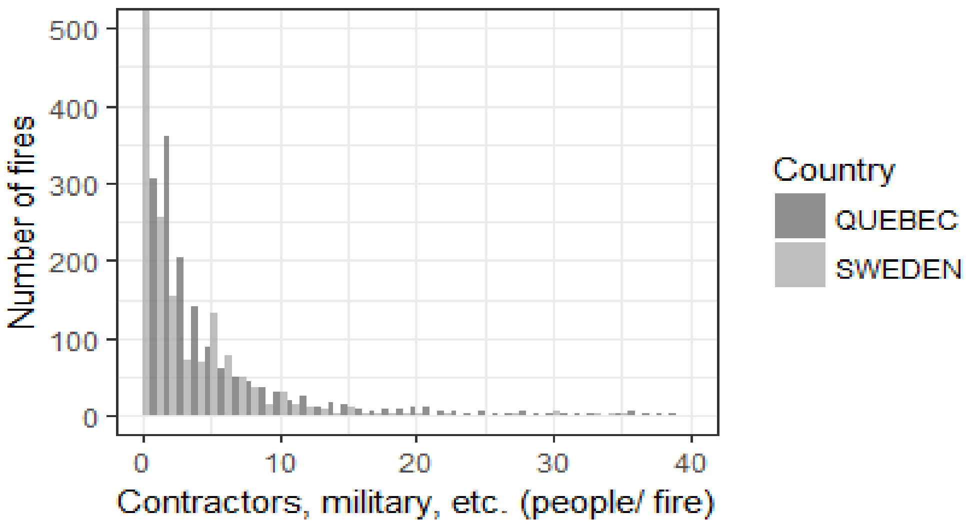

Figure 12 Number of part-time and temporary helpers fighting fire.

The full-time crew in Quebec was smaller than in Sweden. Typically, SOPFEU works in teams of four, for transportation in helicopters or pick-up trucks (Société de protection des forêts contre le feu (SOPFEU), 2018). Quebec's fulltime crew used 2-3 fewer people most of the time, and their total crew size was one less person on average than Sweden (*Table 4*, *Figure 10*, *Figure 12*). However, Sweden's crew worked 219.5 fewer people hours than Quebec's (+/- nine hours standard error, *Table 4*, *Figure 13*).

Figure 13. Total person-hours worked to suppress each fire.

In Sweden, planes were rarely used (less than 2% of all fires, *Figure 17*). In Quebec, planes were used half of the time. Quebec flew 17 hours (+/- 0.5 hours, p<0.001) more than Sweden, to suppress remote fires (*Table 4*). These differences in fire crew may impact the suppression efficiency and cost: more crew or planes may cost more but deploying more resources may more effectively control the fire, reducing total time and area burned. Furthermore, aircraft may be the only way to quickly respond to and suppress remote fires, and a faster response could decrease the suppression difficulty, area burned, and total cost.

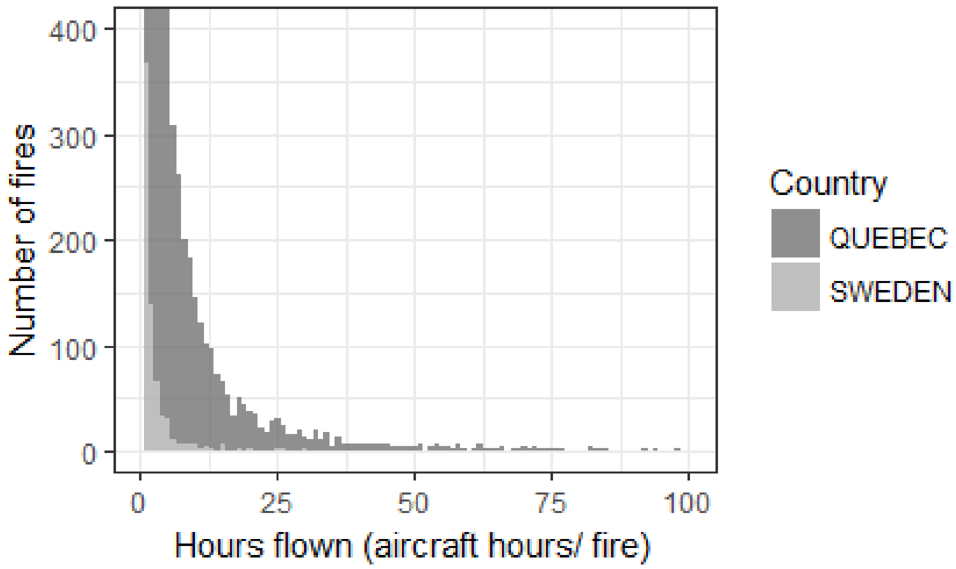

Figure 14. Total flight-hours flown to suppress each fire.

Area burned

In Quebec, 75% of fires were detected at less than 0.1 ha and attacked before reaching 0.4 ha (*Table 5, Figure 15*). Due to the precision of Quebec's database, fires <0.1 ha are reported as zero, so the size of these small fires is unknown. In Sweden, there is no active detection system, but 75% of fires were attacked before spreading beyond 0.005 ha. Sweden's detection and response systems combined were more effective than Quebec's detection system. The effectiveness of the detection system impacts the overall suppression effectiveness, with 75% percent of the fires in Quebec and Sweden being suppressed at 0.6 ha and 0.05 ha, respectively. In total, 44% of Quebec's fires were small, with less than 0.1 hectares burned, whereas 73% of Sweden's fires burned less than 0.1 hectares (*Figure 16*). (The black line on this figure marks the division between large and small fires at 0.1 hectares). Despite more fires in Sweden, their size was smaller, so the annual area burned in Sweden was less than in Quebec.

Table 5. Comparison of area burned from detection, to the start and end of the fire.

	Quebec's IPZ				Sweden		
Value	Detection Size (ha)	Start of Fire (ha)	End of Fire (ha)	Annual area burned (ha)	Start of Fire (ha)	End of Fire (ha)	Annual area burned (ha)
Min	0.0	0.0	0.0	132.7	0.0	0.0	193.7
1st Qu.	0.0	0.0	0.0	2,584.2	0.0	0.0	792.0
Median	0.0	0.1	0.1	27,806.8	0.0	0.0	1,137.7
Mean	2.04	18.85	115.6	106,163.9	0.15	0.92	2,347.4
3rd Qu.	0.1	0.4	0.6	232,443.0	0.0	0.1	2,330.1
Max	5,569	55,000	107,004	386,671.3	300	11,070	12,619.4

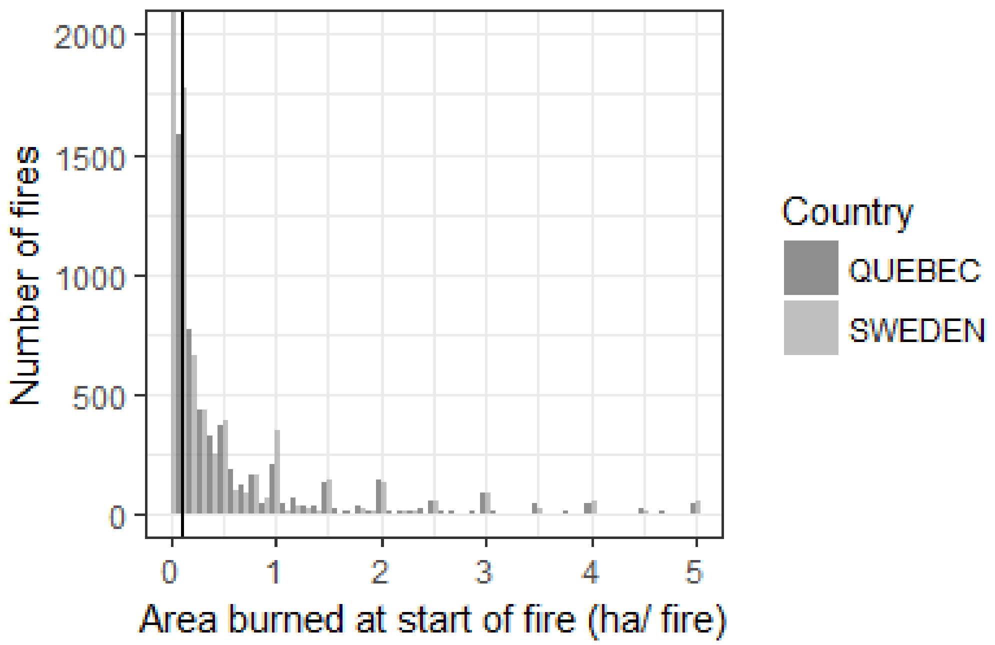

Figure 15. Area burned at the start of firefighter suppression.

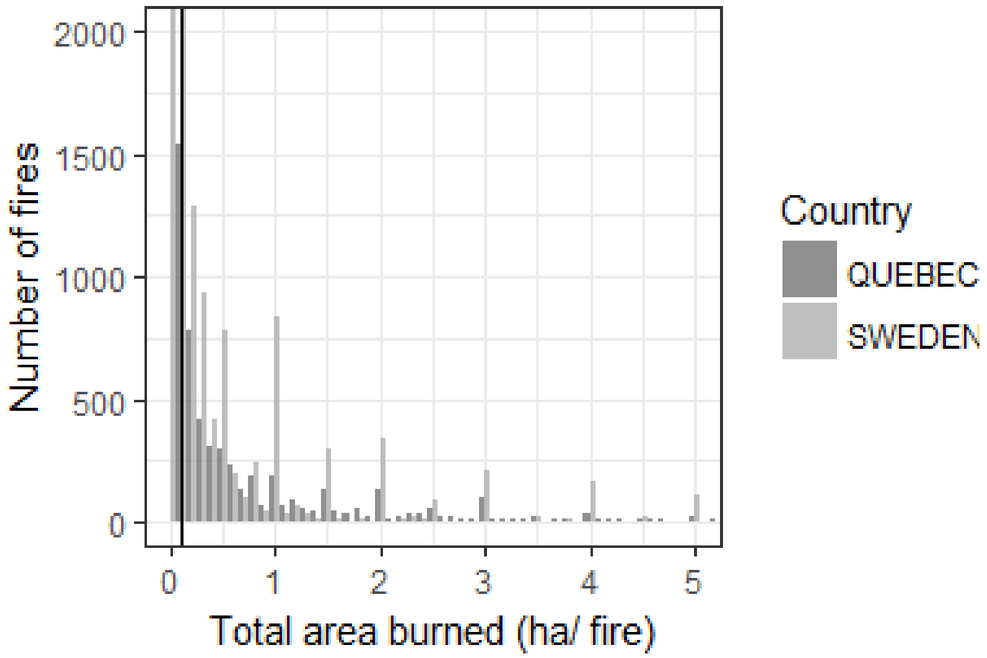

Figure 16. Total area burned by the end of the fire

Suppression cost

The suppression costs were higher in Quebec's IPZ (CAD3.3K/ fire and CAD13,428K/ year median) than Sweden (CAD0.1K/ fire and CAD1,031K/ year median), both for each fire and annually, even though Sweden had more fires than Quebec (Table 6, Figure 17). As the maximum fire costs were at least 1,000 times more expensive than the maximum cost for 75% of the fires, the mean values were higher than the median ones (~ 4.5-8.5 times as much). This means that a few, large fires have a significant impact on the cost. As a reminder, this cost data excludes fixed costs to prepare for and detect fires, as well as equipment costs to fight the fire, and is not inflation corrected. (See Appendix D for the calculations used.)

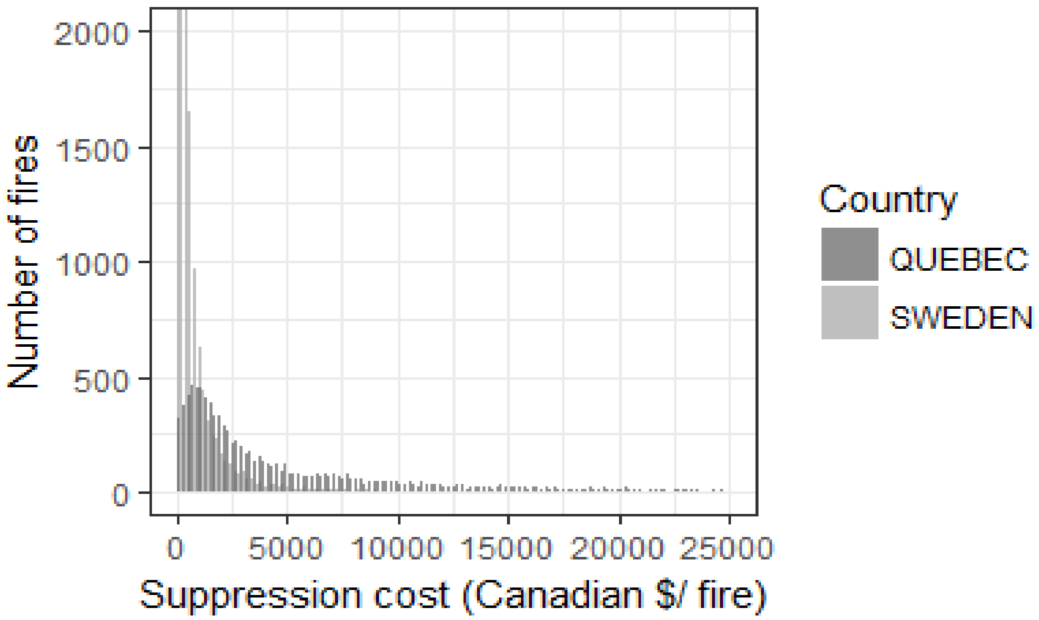

Figure 17. Cost to extinguish each fire

Table 6. Comparison of fire suppression costs, in local currency (Swedish kronor) and Canadian dollars. (1 CAD approx. 7,1 SEK)

	Both	Quebec's IPZ		Sweden			
Value	Wage CAD/hr.	Suppression CAD/fire	Annual kCAD/ Country	Suppression CAD/ fire	Annual kCAD/ Country	Suppression SEK/ fire	Annual kSEK/ Country
Min	15.4	0	831	<1	168	4	1,188
1st Qu.	17.83	1,373	7,769	53	768	391	5,481
Median	19.4	3,333	13,428	115	1,031	852	7,263
Mean	19.53	28,091	21,736	548	1,379	4,068	10,203
3rd Qu.	20.59	10,151	45,573	289	1,302	2,144	9,244
Max	24.34	11,124,461	56,869	2,852,164	4,532	21,021,305	33,894

Financial efficiency

The mean costs per area burned were higher in Quebec's IPZ (CAD23.5K/ ha burned per fire and CAD1.9K/ ha burned per year) than Sweden (CAD2.5K/ ha burned per fire and CAD0.8K/ ha burned per year), both for each fire and annually (*Table 7*), even though Quebec had larger fires than Sweden (*Table* 5). However, at least half the study years had a lower annual cost per area burned in Quebec than Sweden. Assuming all managed land was at risk of burning each year, the cost to protect the forest was less than CAD1.25/ ha saved! Sweden was again more efficient at protecting the land, with a maximum cost of CAD0.15/ ha saved; even though Quebec managed more area, Sweden's total area burned was less. As a reminder, this cost represents the variable suppression costs, excluding equipment, and not the total budget. This analysis excludes fires <0.1 ha.

Table 7. Comparison of fire suppression costs per area lost (area burned, per fire or year) and per area saved (the annual area not burned in the IPZ or the whole of Sweden), in local currency Canadian dollars (Quebec) and for Sweden Canadian $, CAD and SEK (Swedish kronor)

	Quebec's IPZ			Sweden					
Value	CAD/ha per fire	Annual CAD/ha lost	Annual CAD/ha saved	CAD/ha per fire	Annual CAD/ha lost	Annual CAD/ha saved	SEK/ ha per fire	Annual SEK./ ha lost	Annual SEK./ ha saved
Min	0	74	0.18	<1	359	0.01	2	2,686	0.04
1st Qu.	4,358	164	0.17	566	539	0.03	4,153	3,839	0.18
Median	11,311	677	0.29	1,292	924	0.03	9,532	6,624	0.24
Mean	23,501	1,860	0.52	2,496	839	0.04	18,593	6,222	0.33
3rd Qu.	26,784	2,518	0.98	2,742	1,012	0.04	20,329	7,201	0.30
Max	604,722	10,602	1.23	273,249	1,397	0.15	2,008,498	11,267	1.11

Effect on Effectiveness & Efficiency: Linear models

Linear models describing area burned, suppression cost, and suppression efficiency were created (see Appendix F. Best-fit linear models for more details). Each model used 9-16 significant variables to explain the variance (89.85%, 97.96%, & 98.26%, respectively) with AIC likeliness criteria of 2786, 14.73, and 14.73 ($p<0.001$ for all models; $F(43,975)=210.6$ for area burned, $F(23,1549)=3275$ for cost, and $F(23,1549)=3866$ for efficiency). Financial models are more mechanistic than ecological models, hence the models with financial information had better fit (lower AIC) linear regressions. This analysis excluded small fires less than 0.1 hectare. Thus, 6,364 Quebec fires and 10,294 Swedish fires were analyzed. (44% of Quebec's fires and 73% of Sweden's fires were excluded).

Area burned was best described by location, remoteness (population in the region), total suppression effort (suppression cost, total number of people), and climatic variables (*Table 10*). Overall, Sweden had less area burned than Quebec. However, area burned varied significantly within Sweden (ten of seventeen regions were significantly different at $p<0.05$) and Quebec (nine of thirteen bioclimatic zones, $p<0.05$). More populated regions had less area burned (-11.9% decrease in area burned, given a percentage increase in regional population, $p<0.01$). The bioclimatic (vegetative) zones also decreased the area burned; in Quebec, the eastern regions had a lower area burned than the western ones.

Suppression cost increased with the fulltime wage, personnel and aircraft hours worked; location (bioclimatic zone) and number of people working the fire were also significant ($p<0.001$ for all) (*Table 10*). Regional risk factors representing remoteness (amount of forest to protect, population density, etc.) were not significant. Climatic factors were significant but had little impact on cost. Area burned and response time played a small, explanatory role. Overall, suppression cost was lower in Sweden than Quebec ($p<0.001$).

Suppression efficiency linear analysis was like the cost analysis, with a few differences. The financial efficiency of suppression was most impacted by area burned and the fulltime wage (as expected, given the equation used), followed by suppression effort and location of the fire (*Table 10*). Efficiency improved (less cost per area burned) with larger fires. With lower costs, Sweden was more efficient than Quebec ($p<0.001$).

Resources used impacted the area burned, suppression cost, and efficiency. Larger areas burned significantly correlated with more suppression effort – higher suppression cost, more people (fulltime and total people) involved, and longer operations ($p<0.001$ for all) (*Table 10*). However, area burned decreased with total person hours, flight hours, size of crew, and temporary support. A larger fulltime crew had a bigger impact on decreasing area burned than did temporary helpers (-0.41% versus -0.31% decrease given a percentage increase in people, $p<0.01$). Area burned decreased as total hours worked increased, with person hours reducing the area burned more than aircraft hours (-0.66% versus -0.31% decrease given a percentage increase in hours worked, $p<0.001$). Aircraft increased the cost more than personnel did (0.59% versus 0.30% increase in cost given a percentage increase of hours worked, $p<0.001$). With a lower cost and greater effectiveness at reducing area burned, people (total person hours) were more efficient than planes (fire flight hours).

DISCUSSION

This comparative study sought to describe differences between wildfire suppression in Quebec and Sweden, and to understand what effect those differences had on suppression cost, area burned, and suppression efficiency. A handful of hypotheses about their differences in suppression response and effort were posed earlier. The descriptive analysis helped understand the different factors that may impact wildfire suppression in Quebec and Sweden. The statistical models confirmed if these differences were significant and meaningful to the suppression cost, area burned, and efficiency. For the most part these differences were found to be true:

1. **Remoteness.** Fires in Quebec typically occurred in more remote areas than fires in Sweden. However, some Swedish counties represent similar remoteness as Quebec's IPZ. Considering regions within both study areas, population significantly decreased area burned (-11.9% decrease in area burned, given a percentage increase in population, $p<0.001$). More populated areas had more frequent, smaller fires.

2. **Response Time.** Possibly reflecting differences in road networks or distance to the fire, firefighters did take longer to respond in Quebec. The total operation also lasted longer. However, Quebec had a higher standard to meet before the site was considered safe to leave. Response time significantly impacted cost, area burned, and efficiency, but the effect was low compared to the other variables (< -0.1% decrease, per percentage increase of hour, $p<0.05$). Total operation time was significantly related to the area burned (+0.55% increase, per percentage increase of hour, $p<0.001$).

3. **Personnel – resources used**. Contrary to expectations, less resources were used to suppress fires in Quebec. This was due to transportation requirements: four people fit into a helicopter or pickup truck needed to reach remote sites. Taking more people would require more aircraft and equipment, which would increase the cost. In this study, the cost increased +0.11% as the total number of people increased ($p<0.001$).

4. **Personnel – hours worked.** Larger, more remote fires, combined with fewer personnel suppressing the fire, contributed to more hours worked in Quebec than in Sweden. Aircraft hours were also higher, since aircraft were necessary to reach many remote fires.

5. **Effectiveness - area burned.** Fires in Quebec were larger upon arrival and burned more area before being suppressed. Despite actively searching for wildfires, with its lower population density and fewer people to report fires, Quebec fires were detected at a larger size. A larger fire to attack significantly increased the total area burned (+0.5% increase, per percentage increase of hectare burned upon arrival, $p<0.001$). The total area burned increased the cost a little (+0.05%, $p<0.001$), and improved the efficiency (-0.95%, $p<0.001$). Larger fires justified more expenditures to suppress them.

While Quebec had more area burned, fewer people were deployed. The impact of personnel was assessed in the statistical models. Larger fires required more resources to suppress it: the area burned increased +1.22% given a percentage increase in personnel ($p<0.001$). The size of the fire decreased as the number of fulltime and part-time people increased, with fulltime crew being more effective at reducing the area burned (-0.4% versus -0.3%, per percentage increase of personnel, $p<0.01$). As total personnel only modestly effected the cost and efficiency (+0.11% increase given a percentage increase in people, $p<0.001$), it may be better to send more people to attack the fire initially. Given the challenges of reaching remote fires, this would require more aircraft as well.

6. **Financial effectiveness - suppression cost.** Suppression was less effective, with higher cost and area burned, per fire and annually, in Quebec. However, this did statistically differ within each study area.

7. **Financial efficiency (overall resources)**. Contrary to expectations, Quebec was less efficient, with higher costs not offset by the area burned nor the area protected. Quebec does suppress fire to a higher standard, and their aircraft costs include some fixed maintenance costs. However, remote fires may be better to monitor than suppress.

8. **Resource usage - people versus aircraft.** The effect of aircraft versus personnel hours worked was assessed in the statistical models. Aircraft increased the cost more (+0.59% versus +0.30%, $p<0.001$), decreased the area burned less (-0.31 versus -0.66%, $p<0.001$), and increased the cost per area burned more (+0.59% versus +0.3%, $p<0.001$) than personnel. Therefore, it is better to use more personnel than aircraft.

Overall, remoteness played a large role in explaining differences in area burned. A larger regional population significantly decreased area burned (-11.9%, $p<0.01$), but did not significantly impact the cost nor efficiency. With more people in the region, the risk of fire occurring increases. More frequent fires may keep the fuel load and risk of large fires low, as Sweden experienced in the past (Niklasson & Granström, 2000). Furthermore, fires in more populated areas are more likely to be found and reported. The earlier this happens, the sooner the fire can be put out. With better road networks in developed areas, the agency can respond faster. Faster responses decrease total area burned (-0.1%, $p<0.01$) as the fires are smaller when the crew arrives. Attacking larger fires increases the chance that the fires will burn a larger area (+0.5%, $p<0.001$), so it is important to locate wildfires early. The presence of more people in the management area increased the likelihood that fires can be easily suppressed.

The selection of appropriate resources to suppress the fire was critical. It was better to use more people than aircraft hours to suppress the fire quickly, cheaply, and efficiently. As Sweden rarely uses planes, Sweden's fires were smaller, cheaper to extinguish, and more efficient to suppress; however, these values did vary significantly between counties.

Using more resources, (total number of people, person hours, and flight hours), increases the cost, resulting in a poorer efficiency. However, these resources generally help reduce area burned. A fulltime crew was more effective at reducing area burned than using part-time help (-0.41% versus -0.31%, $p<0.01$). Unfortunately, temporary help may be requested only after the fire is too large for the initially deployed resources. The use of more people overall was correlated with larger fires, but a strong, initial effort to suppress the fire decreased the area burned: total person hours decreased the area burned by -0.66%, $p<0.001$. When controlling for area burned, aircraft had a worse effect on the cost and efficiency than person hours did (+0.59% versus +0.3%, $p<0.001$). As aircraft are necessary to suppress remote fires, remote fires may be better to monitor than extinguish, so long as these wildfires are not expected to threaten people.

Despite the assumption in the descriptive analysis, differences within each study area contributed more significantly to differences in cost, area burned, and suppression efficiency than differences between them did: none of the models included “Country,” nor “agency” as significant independent variables. Instead the model used differences between management “region” (Swedish county or Quebec’s IPZ) and vegetative “bioclimatic zone” to explain differences within the two. This is good news for the firefighting agencies in Quebec and Sweden. While the descriptive analysis showed there are differences, these differences in fire response vary within each area and were more significant than if Quebec or Sweden was responsible for the fire. SOPFEU would probably be just as effective and efficient at suppressing fires in Sweden as the Swedish municipalities are, when the conditions for the fire and resources used are the same. Therefore, they can share best management practices to optimize their future approach to wildfire management.

While not explored in much detail in this study, land managers may be able to assist firefighting agencies. In this study, the bioclimatic zones significantly ($p<0.05$ or less), decreased the risk of area burned (-0.31% to -1.55%). Climatic factors impacted this, as the eastern zones of Quebec experienced more rain and had a lower area burned than the other zones. However, differences along the north-south gradient may also reflect differences in vegetation, with more deciduous species located in the south. Land management practices may also affect this. Sweden practices more active forest management than Quebec, so forests in Sweden may have less fuel available to burn than Quebec. Active land management with less fire-prone species may reduce fire risk.

CONCLUSION

The future situation for fire management is dynamic and changing. The risk of severe and uncontrolled wildfires may increase with climate change, as drought and temperatures rise (Flannigan, et al., 2013; Intergovernmental Panel on Climate Change (IPCC), 2013; Flannigan, et al., 2009). At the same time, the population is projected to grow. Although the highest population growth may be in or near urban centers (Bollman & Clemenson, 2008), more people may live in rural areas, currently at risk of wildfire (in the “wildland-urban-interface,” WUI) (McGee, et al., 2015). This may increase the risk of human-caused fire and put more people at risk of wildfires in the future. (Chas-Amil, et al., 2015). With more people to protect and more extreme fire conditions, the challenge to suppress fires will increase. These conditions could increase the area burned and costs to extinguish the fire. It is important to understand the factors that drive area burned, suppression cost, and financial efficiency, and implement efficient ways of suppressing fire. This study furthered the understanding of those factors.

This study described differences between wildfire suppression in Quebec and Sweden, from 1998-2015, and statistically analyzed the effect those differences had on suppression cost, area burned, and suppression efficiency. Cost, area burned, and suppression efficiency were both described in absolute terms, and statistically analyzed to assess the impact of remoteness, response time, personnel, climate, and vegetation. Sweden’s fires were smaller, less expensive, and more efficient to extinguish than Quebec’s, although this did vary within different regions of the country; more populated areas had less area burned. Using personnel to extinguish the fire was cheaper, more effective, and more efficient than using aircraft, however aircraft may be required to reach remote fires before they are uncontrollable. For this reason, remote wildfires may cost too much to justify the resources to suppress them. Regarding personnel, it was better to use a larger, fulltime crew for a strong initial attack than rely on part-time support later. Bioclimatic zones also played a significant role in reducing area burned and should be explored in more detail. Understanding what impacts wildfire suppression can help firefighting managers optimize their approach and respond appropriately in the future.

While firefighting agencies need to consider and plan for potential increases in fire risk, the situation may be more optimistic than projected. In this study, increases in population decreased the area burned more than climatic variables increased it. Historically in Sweden (1650-1860), humans increased the frequency of fires, which decreased the area burned (Niklasson & Granström, 2000). More frequent fires maintain open understories, with less ground litter and brush available to burn. Some wildfire agencies prescribe fire for this reason. Active forest management (to thin or clean the understory) may also decrease the fuel load. Furthermore, the small trees and bushes removed could be used for pulp or biofuel to offset the management cost. While not assessed in this study, Sweden has more active forest management than Quebec. This may have decreased the cost and area burned. Preventative measures to reduce fuel and decrease large fires should be explored in more detail. Since certain vegetative zones reduced area burned, future research should identify these species. Then land managers could plant more of them to decrease the risk of wildfire in the future.

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APPENDIX

Appendix A: Variable list

Table 8. Alphabetical list of variables used in this study, their sources, and some notes. Categories include: area burned, climate, location (management region, bioclimatic zone, agency responsible), personnel (incl. aircraft), regional remoteness (forest cover & population), response time, suppression cost, and suppression efficiency.

Category	Variable	Scale	SWEDEN Source	SWEDEN Notes	QUEBEC Source	QUEBEC Notes
Area burned	Area burned at arrival	Per fire	MSB	Area burned at start of attack.	SOPFEU	Same
	Area burned (total fire)	Per fire	MSB	Reported in +/- 1 m2. Rounded to +/-0.1 ha for comparison with SOPFEU.	SOPFEU	+/-0.1 ha. "Small fires" are 0-0.1 hectares
Climate	Fire date & time (SOS)	Per fire	MSB	1998-2015, Month, day, time of SOS alarm call	SOPFEU	1998-2015, Month, day, time of fire report
	Fire location (GPS)	Per fire	MSB	GPS values reported in SWEREF99 coordinate system. Missing values or GPS points located outside of Sweden corrected to that of the community's centroid.	SOPFEU	GPS coordinates at the fire’s starting spot. Quebec Lambert coordinates system.
	Fire Weather Index (FWI)	Per fire	NRC	Global BioSIM dataset. Uses fire date & GPS.	SOPFEU	Same
	Initial Spread Index (ISI)	Per fire	NRC	Global BioSIM dataset. Uses fire date & GPS.	SOPFEU	Same
	Wind speed (m/s)	Per fire	MSB	Estimated at the fire.	SOPFEU	Wind’s speed at solar noon on the first day (m/s)

Category	Variable	Scale	SWEDEN Source	SWEDEN Notes	QUEBEC Source	QUEBEC Notes
Location	Country	Per country	MSB	“Sweden”	SOPFEU	“Quebec”
	Region	Per region	MSB	21 Swedish counties with joint-agency agreements	SOPFEU	Intensive Protection Zone (IPZ)
	Bioclimatic zone	Per zone	SLU-Mark Info	Three zones: Above 60° latitude is boreal; below is hemi-boreal. West of 14.5° longitude experiences more rain than the east.	Natural Resources Quebec	6x2 zones based on vegetation and climate. Eastern locations get more rain, and southern location are more temperate.
	Firefighting Agency	Per agency	MSB	Each municipality (290) is treated as an independent agency.	SOPFEU	SOPFEU or municipalities
Personnel	Number of fulltime firefighters	Per fire	MSB	Number of people representing the agency	SOPFEU	SOPFEU regular and seasonal employees
	Number of part-time firefighters	Per fire	MSB	Includes military, other firefighting agencies, special support, etc.	SOPFEU	Temporary employees, contractors, agency agreements
	Total person-hours	Per fire	MSB	Total hours worked at the fire.	SOPFEU	Same
	Fire flight-hours	Per fire	MSB	Water bombing & other uses to suppress fire. Rarely used in Sweden.	SOPFEU	Large role in remote fires: transportation, supervision, water bombing, etc. Also used for detection (excluded from study).

Category	Variable	Scale	SWEDEN Source	SWEDEN Notes	QUEBEC Source	QUEBEC Notes
Regional Remoteness	Forest area	Per region	SLU-NFI	Forest area per county. Reported per 1000 ha.	SOPFEU	Forest area in IPZ (ha).
	Total land area	Per region	SLU-NFI	Land area per county. Reported per 1000 ha.	SOPFEU	Land area in IPZ (ha).
	Forest Percentage	Per region	SLU-NFI	Forest/ land area per county. Reported per 1000 ha.	SOPFEU	Forest/ land area in IPZ (ha).
	Population	Per region	SCB	Sum of community populations in the county.	Statistics Canada -> Calculated	Estimated the annual population of Quebec. Assumed the entire population lives in the IPZ.
	Population density	Per region	SCB+SLU-NFI -> Calculated	Sum of community populations per county, divided by the total land per county.	Statistics Canada + SOPFEU -> Calculated	Assumed the entire population of Quebec lives inside the IPZ. Divided by the IPZ area.

Category	**Variable**	**Scale**	**SWEDEN Source**	**SWEDEN Notes**	**QUEBEC Source**	**QUEBEC Notes**
Response time	Time fire reported	Per fire	MSB	Date & time of SOS alarm call. If missing, used time to notify firefighting agency instead.	SOPFEU	Date & time of report. NOTE fires extinguished by Quebec municipalities may be reported afterwards.
	Time attack starts	Per fire	MSB	Date & time the attack starts.	SOPFEU	Same
	Time attack ends	Per fire	MSB	Date & time the attack ends.	SOPFEU	Date & time the fire is declared out. Includes mop-up.
	Response time	Per fire	MSB	Time elapsed from SOS alarm to start of attack. Includes time to answer the call, get ready, and drive to the fire.	SOPFEU -> Calculated	Time elapsed from fire report to start of attack. Includes time to answer the call, get ready, and drive to the fire.
	Total incident time	Per fire	MSB	Time from alarm to clean up completed. May not include mop-up.	SOPFEU -> Calculated	Time from fire reported to declared out. Includes mop-up.
Suppression Cost	Fulltime wage	Per hour	SCB -> Calculated	Average fulltime wages of 2005-2016 were linearly projected to 1998. NOT inflation corrected (SEK/ hr.)	SOPFEU	CAD/ hr., with and without benefits. Listed without benefits in database.
	Costs to extinguish the fire	Per fire	MSB, SCB + SOPFEU -> calculated	See Appendix B, calculations. Reported in tkr and CAD (for comparison with Quebec).	SOPFEU	Includes people & aircraft. Air tanker cost is estimated as total costs/ fires that year.

Category	Variable	Scale	SWEDEN Source	SWEDEN Notes	QUEBEC Source	QUEBEC Notes
Suppression Efficiency	Costs/ area burned	Per fire	MSB, SCB + SOPFEU -> Calculated	Variable suppression cost divided by area burned	SOPFEU -> Calculated	Same
	Costs/ area protected	Annual	MSB, SCB, SLU-NFI + SOPFEU -> Calculated	Variable suppression cost divided by area protected (area managed – area burned)	SOPFEU -> Calculated	Same

Appendix B: Assumptions, calculations, and errors

Area burned (ha/ fire)

Area burned at the start of the fire represents the area burned upon arrival of the firefighters.

Area burned at the end of the fire represents the total area burned by the fire.

For both values, Sweden estimates area burned +/- 1 m^2 (+/- 0.0001 ha). Quebec records area burned +/- 0.1 ha, with fires smaller than 0.1 ha (43% of Quebec fires) recorded as zero area burned. Hence, the size of small fires is known in Sweden, but not known in Quebec. To compare these at the same precision, Sweden's fires were rounded to the nearest 0.1 ha.

Climatic variables: Fire Weather Index (FWI), Initial Spread Index (ISI), & wind.

The fire weather index (FWI) is a value representing the overall climatic risk of fire; it combines the initial spread index, the drought index, and other measures of dryness to assess the overall fire hazard (Natural Resources Canada (NRC) , 2018). The initial spread index (ISI) represents how fast the fire may move; it is an assessment of wind speed and air humidity. The drought index represents the severity of the fire; it is based on the depth of water in the soil. SOPFEU provided these values directly.

A global weather dataset using the software BioSIM (Natural Resources Canada (NRC) , 2018), was used to lookup the historical FWI & ISI values for Sweden. This database needed the GPS location of the fire, its date, and its elevation (assumed to be zero). Sweden reported these data with the coordinate system SWEREF-99 TM, which were converted using ArcGIS to the RT90 coordinate system for use with the software. Of Sweden's fires, 27.65% were missing their GPS location. An additional 12.8% were located outside of the country's borders (e.g., far into the Baltic Sea, or the middle of Norway) - this was likely due to using a different coordinate system than the one specified by MSB. Both of these errors (40.45% of Swedish fires) were corrected with the centroid GPS of the community responsible for suppressing the fire. While these corrected values do not represent the local climate, they do at least represent the correct regional climate. These GPS were used with BioSIM, and the climatic data that matched the start date of the fire were kept. Some locations (1.5% of Sweden's fires) lacked climatic data for that location's date and were treated as null values in the statistical model.

Incident time (hours/ fire)

Incident time = time from SOS report to end of operation

In Quebec, this represents the time the fire was reported, to the time the fire was declared out. This includes mop-up to ensure the fire is fully extinguished, with no embers glowing, so the fire is unable to restart. This value is calculated by subtracting the date and time the fire is reported from the date and time the fire is finished. Negative values (1.5% of fires) result when the fire is reported after it is extinguished – as is the case when the Quebecois municipalities suppress the fire. These values are excluded.

In Sweden, this represents the time of the SOS call, to the time the operation ended. Sometimes the fire is still smoldering when the operation ends, with the mop-up period left for the property owner to monitor. If the fire restarts, it is recorded as a new fire incident.

In Sweden, this time is recorded twice in the database: once directly as incident total time, and once as a calculation from the date and clock times reported for the SOS and end of operation. These values exactly match only 21% of the time, but they match within 5 minutes, 91% of the time; within 10 minutes, 97.5% of the time; and within 15 minutes, 98.5% of the time. Presumably the directly recorded time is an estimate by the firefighter, whereas the clock time is more exact. However, there are many typos in the clock time (inconsistencies in format: year/ month/ day, or day/ month/ year, or month/ day/ year, plus what appear to be mistakes where a physically close number is typed instead) which make the estimate more trustworthy. For this study, the value that was reported directly is used, unless that value is missing (1% of fires). As all Swedish fires in this database are suppressed, this is believed to be an error. Then the clock times are used to calculate the total incident time. For those that are still missing, as well as those operations lasting over a month (including two year-long values, believed by MSB to be a typo in the date), the average incident time for that year and community is used.

Person hours, (hours/ fire)

Person hours = total full-time (FT) and part-time (PT) hours worked, per person

Calculated for the time from the notification of a fire to the end of the operation.

$$Person\ hours = \sum_{people=1}^{All} (Person * Hours)_{FT} + (Person * Hours)_{PT}$$

Both countries provided the fulltime and part-time person-hours.

The data was checked for internal validity with the database, using this test:

$$(Incident - Report)\ Time < Person\ Hours < Incident\ Time * People\ Worked_{FT+PT}$$

This test assumes that the minimum time spent working the fire is one person working the entire attack time. The report time is not included in the lower limit as SOPFEU may not respond to a fire for days if there is a higher priority fire. The maximum time spent at the fire is if everyone works the whole time.

For Quebec, 45% of the data passed this test, even when subtracting long response times. For safety reasons, SOPFEU does not work at night, so fires that last multiple days would not have a person working the whole time. Hence, the lower limit may be hard to define. Fires that exceed the upper limit are 26.5%.

For Sweden, 55% of the data passed this test, with only 0.1% exceeding the upper limit. For both countries, person hours are presumably used to pay people for their work, so these values are assumed to be correct. This would be increasingly true in Sweden as municipalities digitize their records.

Response time (hours/ fire)

Response time = time from SOS report to start of attack

In Quebec, this value is calculated by subtracting the date and time the fire is reported from the date and time the fire is attacked. Null and zero values (2.25% of fires) are assumed to be fires that are reported out, or suitably small, with poor conditions for the fire, that they extinguished themselves. Hence, no response was needed. Negative values (10.75% of fires) may result when the fire is reported after it is attacked – as is the case when the Quebecois municipalities suppress the fire. These values are excluded. Unlike in Sweden, long response times (7% >= 10 hours) are valid and kept. These fires may have been reported at night or when SOPFEU resources are busy attacking a higher priority fire.

In Sweden, this value is reported three ways: once directly as response time, once as the summation of activities describing the response (time to handle the call, notify the firefighters, get ready and drive to the site, and assess the situation on-site before starting the attack), and once as the difference in time from the SOS call to the start of the attack. For this study, the directly reported response time is used, unless this value is missing, zero, or negative (13.5% of fires). Then the summation is used to fill these values (11.5% of fires), followed by the difference in clock time (1% of fires). The summation had higher internal validity with the directly reported response time (52% versus 14% match exactly; 97.75% versus 60% were within 15 minutes), hence the summation was used to correct the missing values first. Fires that still have a response time less than zero (1% of fires) are replaced with the average for that community and year. Like incident time, there were many known typos in the clock time. MSB believed that any responses lasting over three hours were mistakes (0.4% of fires) – this study replaced those over five hours with the community's average response time that year (0.25% of fires).

Suppression efficiency (cost/ area)

Suppression efficiency is calculated two ways:

1. Cost to extinguish the fire/ area burned (per fire)
2. Annual cost to extinguish the fire / area protected (annually), where

$$Area\ protected = Forest\ area\ managed - Forest\ area\ burned$$

Known data:

See "suppression cost" and "area burned" for these per-fire variables.

In Quebec, the area managed is the size of the forest in the IPZ in 2014: 46,719,784 ha. While the amount of forest and land area is known for the entire study period (1998-2015, standard deviation +/- 2,604Kha, average 50,006Kha, +/- 5%), improvements in remote sensing technology mean that the more recent measurements are more accurate.

In Sweden, the area managed is the total forest land in the country in 2014: 30,651,000 ha. This has been measured to the nearest thousand hectare from 2005-2014, with less than 0.5% change between the years (standard deviation +/- 149.5Kha, average 30,602.5Kha).

Assumptions:

For this study, changes in forestland between years from 1998-2015 is assumed negligible and ignored, despite some gains and losses from year-to-year in forestland. The most recent value known for both areas was used instead.

The annual area protected assumes that all managed forest is at risk of burning that year. However, if all fires burned without suppression efforts, they would probably not burn the entire management area. The cost value also represents a minimum value, as it excludes fixed costs. Together, this means that the financial efficiency of protection represents a minimum cost for the maximum area protected – a best-case scenario.

Quebec population

Annual population of Quebec = 59,976.64*(Year-1990) + 6,785,794.09 (R^2 = 97%)

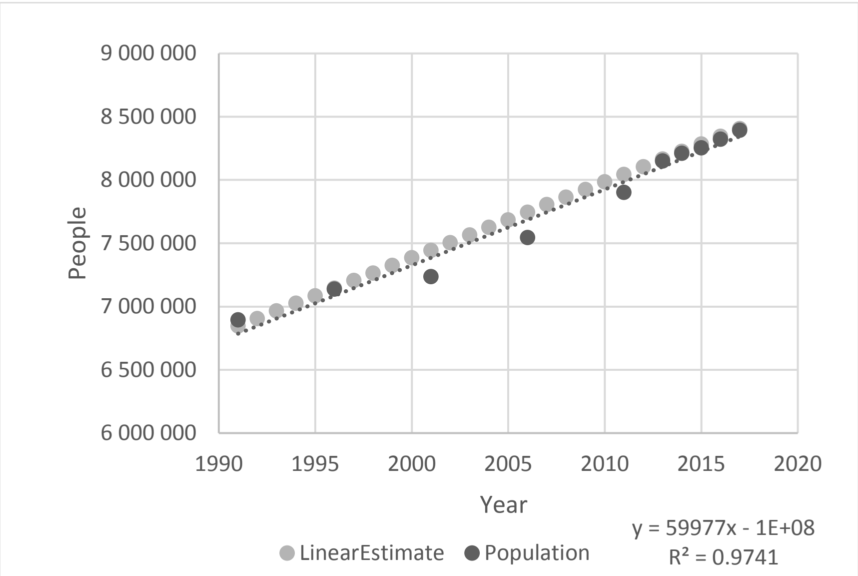


Figure 18. Quebec population growth from 1990-2017.

Known data:

Statistics Canada provided the population census for every 5 years from 1991-2011, and every year from 2013-2017 (*Figure 18*).

Assumptions:

The linear relationship describes the data well-enough to estimate the annual population of Quebec for this study period.

Sweden suppression costs, per fire:

$$Suppression\ Costs = Personnel + Aircraft + Equipment\ Costs$$
$$Suppression\ Costs = Personnel + Aircraft + \cancel{Equipment\ Costs}$$
$$Suppression\ Costs = FTWage * (FT + PT.PersonHrs) + (FlightHrs * Rent)$$

Known data:

Fulltime (FT) and part-time (PT) person-hours worked, per fire

Flight hours, per fire

Full-time firefighting wage, 2005-2016 (Sweden) and 1998-2015 (Quebec)

Assumptions:

Equipment: costs assumed to be negligible.

Personnel: assumed no overtime pay; part-time person (including military and volunteer support) paid like a full-time person.

Currency assumptions:

Aircraft rent:

10K SEK/ hour – based on one community’s response, or

1360 CAD/hour to contract a helicopter in Quebec, an average estimate based on high variability in helicopter type and usage during 1998-2015

FT wage:

As described in Table 9.

The Swedish values from 1998-2004 were estimated based on the linear relationship of wages during 2005-2016: $FTWage = 4.5345 * (Year - 2004) + 138.49$ (R2 = 98.9%). This is a cost of living increase of about +3%/ year.

The Canadian values were given by SOPFEU, with a similar cost of living increase. This hourly rate excludes benefits.

Table 9. Hourly wage of fulltime firefighters in Swedish krona (SEK, kr.) and Canadian Dollar (CAD) during the study period.

YEAR	SEK kr./ hour	CAD/ hour
1998	111	15.40
1999	116	16.44
2000	120	16.88
2001	125	17.32
2002	129	17.83
2003	134	18.37
2004	138	18.37
2005	143	19.40
2006	147	19.79
2007	148	20.19
2008	159	20.59
2009	164	20.59
2010	167	20.59
2011	171	21.98
2012	175	22.42
2013	179	22.42
2014	184	23.86
2015	188	24.34
2016	191	----

Appendix C. Log-normal graphs

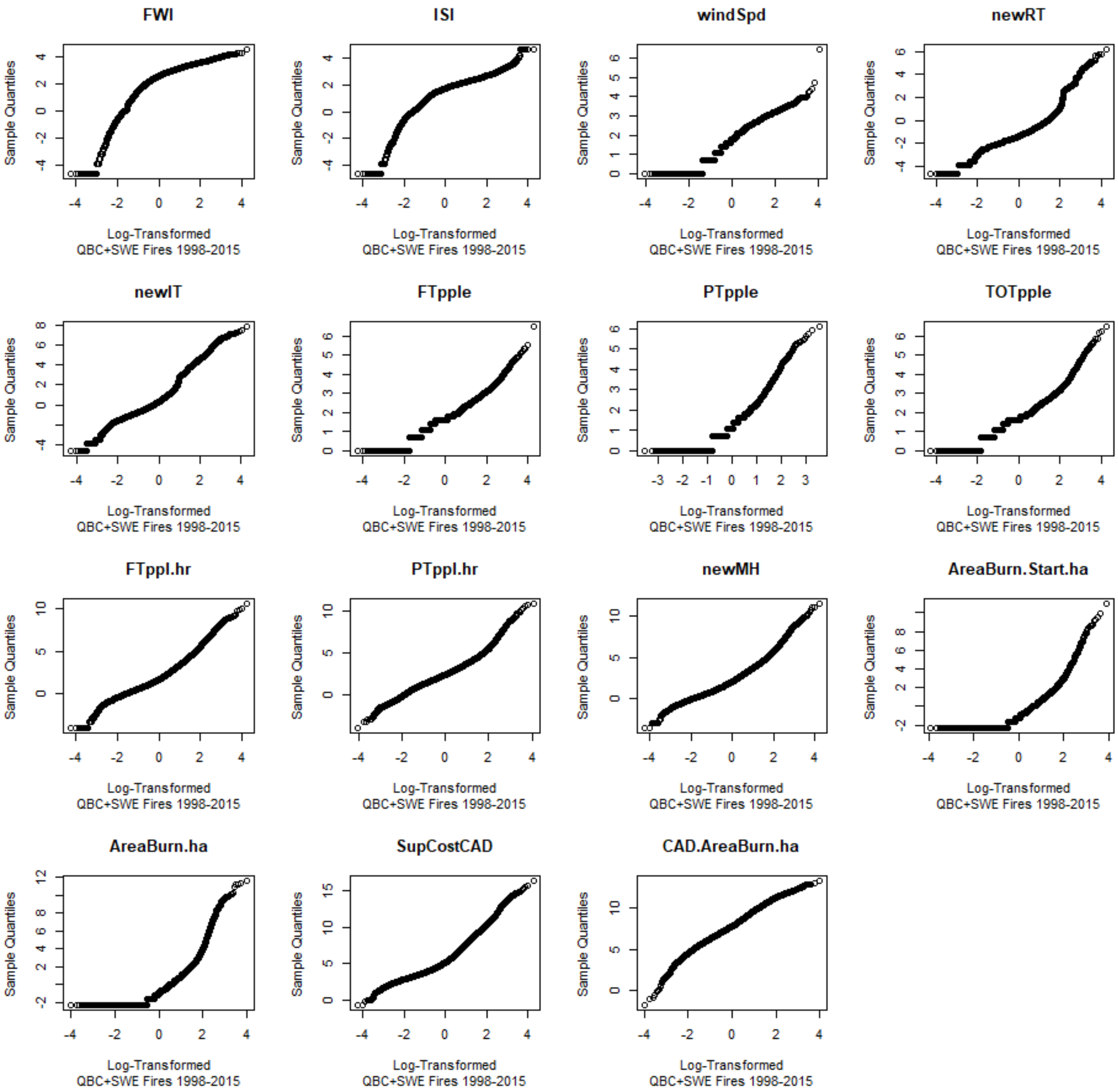


Figure 19. Lognormal data for each fire variable.

Appendix D. Best-fit linear models

This global model lists all the variables tested for significance and best fit:

```
global.model<-lm(log(Y*)~log(newMH)+log(PTppl.hr)+log(FTppl.hr)+log(FireFlightHr)
    +log(PTpple)+log(FTpple)+log(TOTpple)+log(FTwageCAD)
    +log(AreaBurn.Start.ha)+log(newRT)+log(newIT)+log(AreaBurn.ha)+size
    +log(LandArea.ha)+log(ForestArea.ha)+log(PerForest)+log(PopDens.ha)+log(RegPop+
    Country +region +Agency +
    log(FWI)+log(ISI)+log(windSpd)+BioClimateZone, BothFires)
```

*Y = Suppression cost, area burned, or suppression efficiency

Variable List *in order of the above global model*

Personnel

newMH = total person hours worked (Swedish values corrected)
PTppl.hr = part-time hours worked
FTppl.hr = fulltime hours worked
FireFlightHr = aircraft hours flown
PTppl = part-time and temporary helpers suppressing the fire
FTppl = size of fulltime crew
TOTppl = includes fulltime and part-time people
FTwageCAD = fulltime firefighter wage, in Canadian $/ hour

Area & Time

AreaBurn.Start.ha = area burned at the start of the fire, in hectares
newRT = hours from SOS report to arrival of suppression crew (Swedish values corrected)
newIT = total incident hours, from SOS to end of operation (Swedish values corrected)
AreaBurn.ha = total area burned by the fire, in hectares
Size = small or large (>0.1 ha) area burned

Regional Factors

LandArea.ha = size of IPZ or county managed for suppression, in hectares
ForestArea.ha = size of IPZ or county forest managed for suppression, in hectares
PerForest = percentage of forest per land area managed
PopDens.ha = population density of the area managed, per hectare
RegPop = population in the area managed

Location

Country = Sweden or Quebec
Region = IPZ (Quebec) or county (Sweden)
Agency = SOPFEU, or municipality (Quebec or Sweden)

Climate

FWI = fire weather index
ISI = initial spread index
windSpd = wind speed
BioClimateZone = a vegetative and climatic division of Quebec (6 zones, split into east or west) and Sweden (3 zones – north, and south split into east or west)

BothFires = the database containing fires of Quebec and Sweden, 1998-2015

Table 10. Summary of linear models showing the percentage increases (+/- standard error) of area burned, suppression cost and efficiency, given a 1% increase in the independent variable.

Category	**Independent variables**	**Area Burned (ha)** **R2 = 89.85%** **AIC =2786**	**Area Burned Rank**	**Suppression Cost (CAD)** **R2 = 97.96%** **AIC = 14.73**	**Cost Rank**	**Suppression Efficiency (CAD/ha)** **R2 = 98.26%** **AIC = 14.73**	**Efficiency Rank**
Location	**Country**	**Sweden smaller** **(See region)**	**NA**	**Sweden cheaper** **(See bioclimatic zone)**	**NA**	**Sweden more efficient** **(See bioclimatic zone)**	**NA**
	Region	Sweden varies: -20.5% to +22.6%. 10 of 17 zones* Quebec +38.6%***	1	NA	NA	NA	NA
	Bioclimatic zone	Varies -0.31% to -1.55%. Quebec's eastern zones are lower than western ones. 9 of 13 zones*	3	Sweden: -0.57% to -0.61%***. Quebec: 2E +0.41%*** 3E +0.31%*** Others: p>0.1	3	Sweden: -0.57% to -0.61%***. Quebec: 2E +0.41%*** 3E +0.31%*** Others: p>0.1	4
Personnel	**Total person hours (hr./ fire)**	-0.66% +/- 0.14%***	8	0.30% +/- 0.02%***	4	0.30% +/- 0.02%***	5
	Full-time person hours (hr. /fire)	0.19% +/- 0.07%**	14	NA	NA	NA	NA
	Part-time person hours (hr./ fire)	p>0.1	NA	p>0.1	NA	p>0.1	NA
	Fire flight hours (hr./ fire)	-0.31% +/- 0.08%***	13	0.59% +/- 0.01%***	2	0.59% +/- 0.01%***	3
	Total number of people (people/ fire)	1.22% +/- 0.23%***	4	0.11% +/- 0.02%***	5	0.11% +/- 0.02%***	6
	Full-time crew size (people/ fire)	-0.41% +/- 0.14%**	11	p>0.05	NA	p>0.05	NA

	Part-time helpers (people/ fire)	-0.31% +/- 0.11%**	12	NA	NA	NA	NA
Suppression Cost	**Total suppression cost (CAD/ fire)**	1.20% +/- 0.11%***	5	Excluded	NA	Excluded	NA
	Full-time wage (CAD/ hr.). Not inflation corrected	Excluded	NA	0.75% +/- 0.08%***	1	0.75% +/- 0.08%***	2
Response time	**Response time (hr./ fire)**	-0.07% +/- 0.02%**	16	-0.01% +/- 0.00%*	9	-0.01% +/- 0.00%*	9
	Total incident time (hr./ fire)	0.55% +/- 0.06%***	9	NA	NA	NA	NA
Area burned	**Area burned at start of attack (ha/ fire)**	0.50% +/- 0.02%***	10	NA	NA	NA	NA
	Total area burned (ha/ fire)	Excluded	NA	0.05% +/- 0.00%***	8	-0.95% +/- 0.00%***	1
Regional Remoteness	**Land area (ha)**	NA	NA	NA	NA	NA	NA
	Forest area (ha)	NA	NA	NA	NA	NA	NA
	Percentage forest area	NA	NA	NA	NA	NA	NA
(values per county or IPZ)	**Population protected**	-11.94% +/- 1.54%**	2	NA	NA	NA	NA
	Population density (people/ ha)	NA	NA	NA	NA	NA	NA
Climatic risk	**Fire weather index (FWI)**	-0.75% +/- 0.13***	7	0.07% +/- 0.02%**	6	0.07% +/- 0.02%**	7
	Initial spread index (ISI)	0.83% +/- 0.13%***	6	-0.07% +/- 0.02%**	7	-0.07% +/- 0.02%**	8
	Wind speed (m/s)	-0.11% +/- 0.06%*	15	NA	NA	NA	NA

Rank “1” gives the largest percentage increase of the independent variable given a percentage increase of the dependent variable.
P-value significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05.
“NA” variables were excluded from the best model by glmulti.

Area burned (per fire)

Including suppression cost as an independent variable.

glmulti.analysis

Method: g / Fitting: lm / IC used: aic
Level: 1 / Marginality: FALSE
From 100 models:
Best IC: 2786.1574104118

Best model:

[1] "log(AreaBurn.ha) ~ 1 + region + BioClimateZone + log(SupCostCAD) + "
[2] "   log(newMH) + log(PTppl.hr) + log(FTppl.hr) + log(FireFlightHr) + "
[3] "   log(PTpple) + log(FTpple) + log(TOTpple) + log(AreaBurn.Start.ha) + "
[4] "   log(newRT) + log(newIT) + log(ForestArea.ha) + log(RegPop) + "
[5] "   log(FWI) + log(ISI) + log(windSpd)"

Evidence weight: 0.0537683271425155
Worst IC: 2902.00527024389
20 models within 2 IC units.
19 models to reach 95% of evidence weight.
Convergence after 1050 generations.
Time elapsed: 1.84425984111097 minutes.

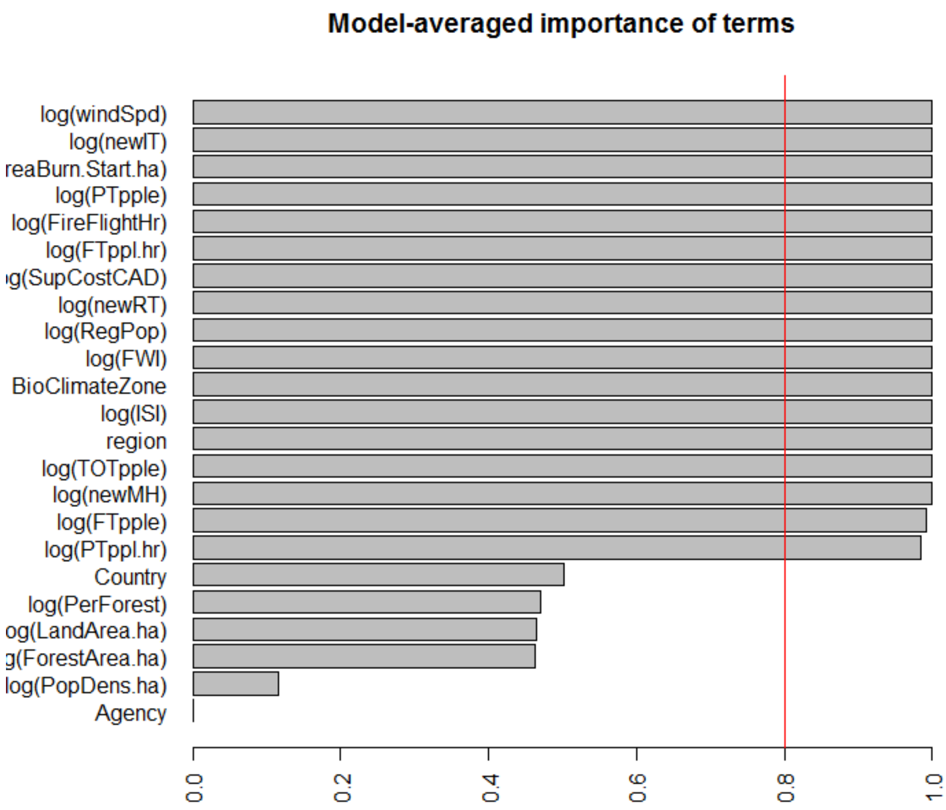


Figure 20. The importance of different variables on the area burned model results.

Revised best model summary

Excluding total land area, total forest area, and percentage of forest.

R^2 = 89.85%, p<0.001, AIC = 2786.157

lm(formula = log(AreaBurn.ha) ~ 1 + region + BioClimateZone + log(SupCostCAD) + log(newMH) + log(PTppl.hr) + log(FTppl.hr) + log(FireFlightHr) + log(PTpple) + log(FTpple) + log(TOTpple) + log(AreaBurn.Start.ha) + log(newRT) + log(newIT) + log(RegPop) + log(FWI) + log(ISI) + log(windSpd), data = BothFires)

Residuals

Min	1Q	Median	3Q	Max
-3.0499	-0.5453	-0.0936	0.4731	6.0199

Coefficients: (2 not defined because of singularities)

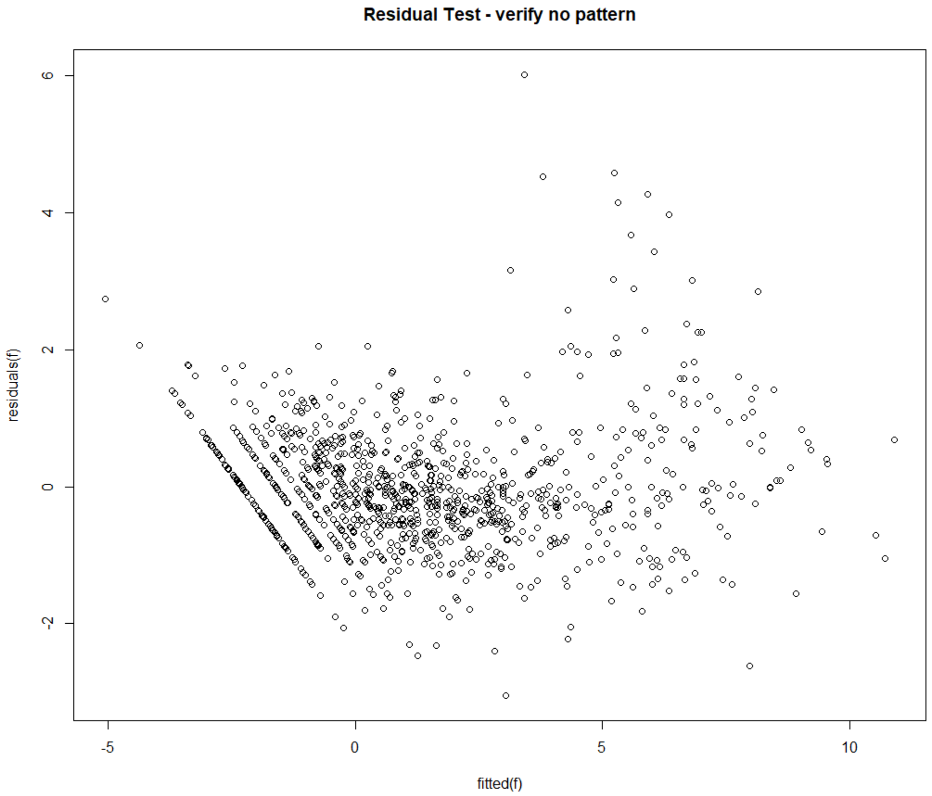
	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	139.93316	19.16150	7.303	5.85e-13	***
regionGävleborg	0.17383	0.85474	0.203	0.838888	
regionGotland	-20.48689	2.72479	-7.519	1.25e-13	***
regionHalland	0.69850	0.87861	0.795	0.426807	
regionJämtland	-6.75552	1.65182	-4.090	4.67e-05	***
regionJönköping	1.54086	0.79993	1.926	0.054363	
regionKalmar	-3.35635	1.17755	-2.850	0.004460	**
regionKronoberg	-5.61273	1.07560	-5.218	2.21e-07	***
regionNorrbotten -	1.12580	0.87337	-1.289	0.197696	
regionÖrebro	1.08793	1.33271	0.816	0.414515	
regionÖstergötland	4.80197	1.48034	3.244	0.001219	**
regionQBCSupZone	38.60738	5.26026	7.339	4.52e-13	***
regionStockholm	22.58235	3.21851	7.016 4	.26e-12	***
regionUppsala	3.41899	1.35703	2.519	0.011912	*
regionVästerbotten	-0.77834	0.85964	-0.905	0.365466	
regionVästernorrland	-2.75852	0.83432	-3.306	0.000980	***
regionVästmanland	-1.18138	1.09181	-1.082	0.279505	
regionVästra Götaland	20.14829	2.75822	7.305	5.77e-13	***
BioClimateZone2E	-1.22207	0.48077	-2.542	0.011179	*
BioClimateZone2W	-0.38192	0.30378	-1.257	0.208978	
BioClimateZone3E	-0.93928	0.28423	-3.305	0.000986	***
BioClimateZone3W	-0.89857	0.25342	-3.546	0.000410	***
BioClimateZone4E	-1.23301	0.29824	-4.134	3.87e-05	***
BioClimateZone4W	-1.16209	0.25702	-4.521	6.90e-06	***
BioClimateZone5E	-1.55166	0.28252	-5.492	5.07e-08	***
BioClimateZone5W	-0.94896	0.24730	-3.837	0.000132	***
BioClimateZone6E	-1.15492	0.25232	-4.577	5.32e-06	***
BioClimateZone6W	-0.73658	0.24730	-2.979	0.002968	**
BioClimateZoneN	NA	NA	NA	NA	
BioClimateZoneSE	-0.31344	0.65350	-0.480	0.631594	
BioClimateZoneSW	NA	NA	NA		NA

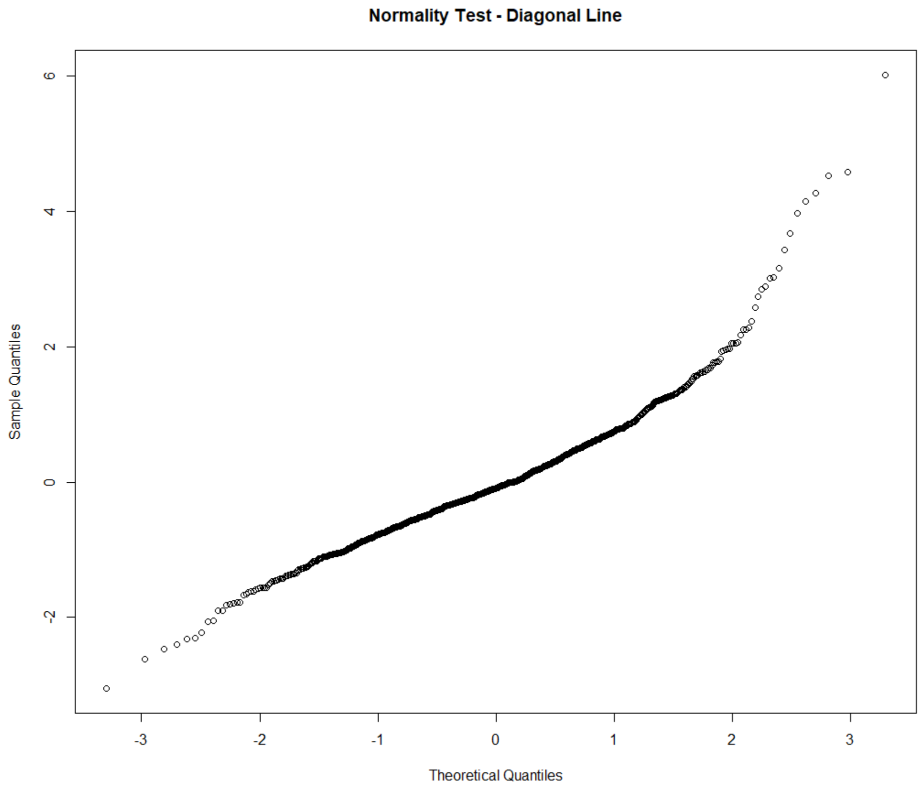
log(SupCostCAD)	1.20117	0.10868	11.052	< 2e-16	***
log(newMH)	-0.65622	0.14329	-4.580	5.26e-06	***
log(PTppl.hr)	0.06852	0.06626	1.034	0.301377	
log(FTppl.hr)	0.19285	0.07436	2.593	0.009648	**
log(FireFlightHr)	-0.30928	0.08001 -	3.866	0.000118	***
log(PTpple)	-0.31197	0.11094	-2.812	0.005021	**
log(FTpple)	-0.41186	0.14055	-2.930	0.003464	**
log(TOTpple)	1.22197	0.23469	5.207	2.34e-07	***
log(AreaBurn.Start.ha)	0.49842	0.02267	21.984	< 2e-16	***
log(newRT)	-0.06591	0.02221	-2.967	0.003080	**
log(newIT)	0.54526	0.05736	9.507	< 2e-16	***
log(RegPop)	-11.94107	1.54138	-7.747	2.35e-14	***
log(FWI)	-0.74934	0.12884	-5.816	8.17e-09	***
log(ISI)	0.83041	0.12868	6.453	1.72e-10	***
log(windSpd)	-0.11348	0.05702	-1.990	0.046851	*

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.9287 on 975 degrees of freedom
(49338 observations deleted due to missingness)
Multiple R-squared: 0.9028, Adjusted R-squared: 0.8985
F-statistic: 210.6 on 43 and 975 DF, p-value: < $2.2e^{-16}$

Verifying assumptions





igure 21. Area burned assumptions for the linear analysis were verified for linearity, homoscedasticity, and normality tests using residual graphs.

Suppression cost

Including area burned as an independent variable.

glmulti.analysis

Method: g / Fitting: lm / IC used: aic
Level: 1 / Marginality: FALSE
From 100 models:
Best IC: 13.8693042628914

Best model:

[1] "log(SupCostCAD) ~ 1 + Country + BioClimateZone + log(newMH) + "
[2] "   log(PTppl.hr) + log(FireFlightHr) + log(FTpple) + log(TOTpple) + "
[3] "   log(FTwageCAD) + log(newRT) + log(newIT) + log(AreaBurn.ha) + "
[4] "   log(LandArea.ha) + log(FWI) + log(ISI)"

Evidence weight: 0.124926255437329
Worst IC: 191.928517315101
11 models within 2 IC units.
13 models to reach 95% of evidence weight.
Convergence after 960 generations.
Time elapsed: 2.70271400749683 minutes.

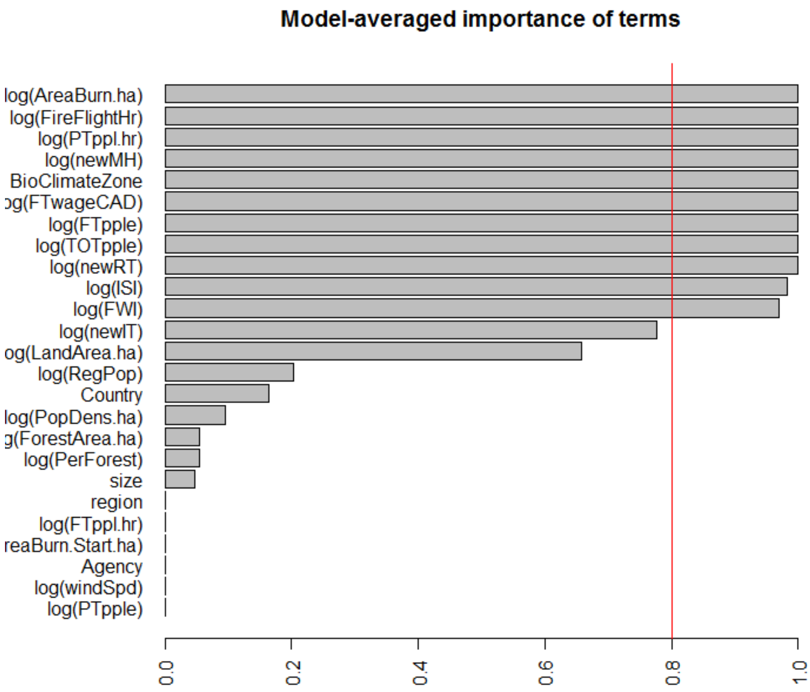


Figure 22. The importance of different variables on the suppression cost model results.

Revised best model summary

Excluding total incident time, total land area, total forest area, and country.

R^2 = 97.96%, p<0.001, AIC = 14.73193

lm(formula = log(SupCostCAD) ~ 1 + BioClimateZone + log(newMH) + log(PTppl.hr) + log(FireFlightHr) + log(FTpple) + log(TOTpple) + log(FTwageCAD) + log(newRT) + log(AreaBurn.ha) + log(FWI) + log(ISI), data = BothFires)

Residuals:

Min	1Q	Median	3Q	Max
-0.82802	-0.14193	-0.03373	0.09837	2.01065

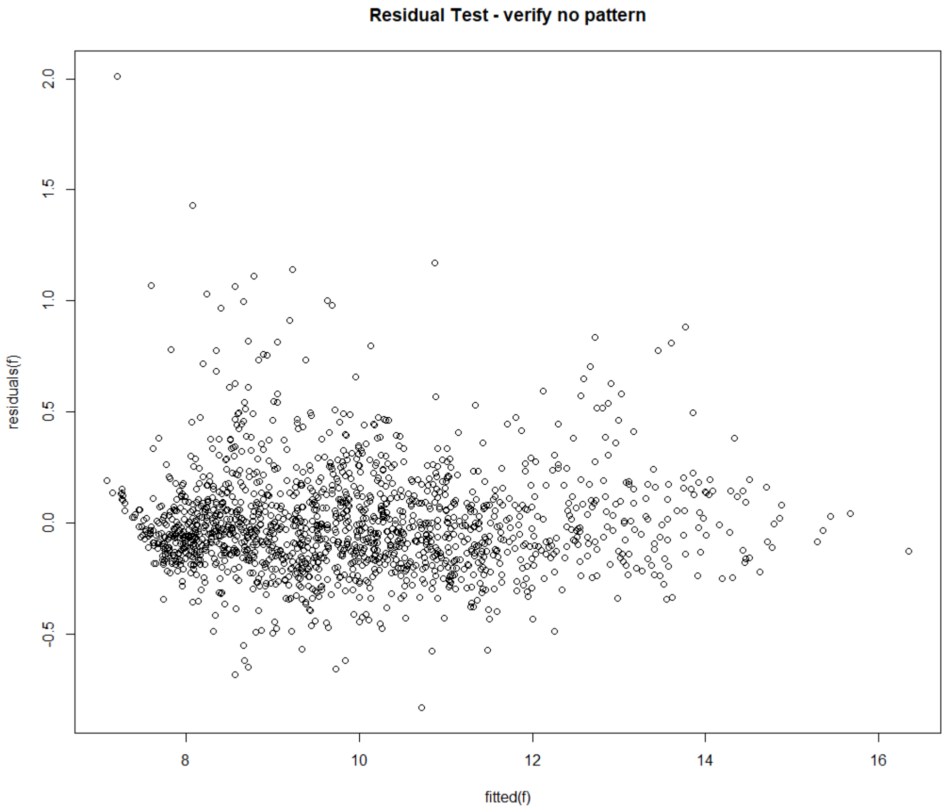
Coefficients

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	4.811335	0.253089	19.010	< 2e-16	***
BioClimateZone2E	0.407497	0.114786	3.550	0.000397	***
BioClimateZone2W	-0.067235	0.076607	-0.878	0.380259	
BioClimateZone3E	0.306876	0.070385	4.360	1.39e-05	***
BioClimateZone3W	-0.074674	0.063416	-1.178	0.239168	
BioClimateZone4E	0.109428	0.074540	1.468	0.142297	
BioClimateZone4W	-0.076987	0.064634	-1.191	0.233790	
BioClimateZone5E	0.102452	0.070549	1.452	0.146647	
BioClimateZone5W	-0.054532	0.061684	-0.884	0.376797	
BioClimateZone6E	-0.022767	0.062931	-0.362	0.717566	
BioClimateZone6W	-0.018495	0.061593	-0.300 0	.764002	
BioClimateZoneN	-0.598061	0.065790	-9.090	< 2e-16	***
BioClimateZoneSE	-0.569978	0.069564	-8.194	5.25e-16	***
BioClimateZoneSW	-0.613392	0.068639	-8.936	< 2e-16	***
log(newMH)	0.295586	0.016513	17.900	< 2e-16	***
log(PTppl.hr)	-0.008222	0.010222	-0.804	0.421301	
log(FireFlightHr)	0.593603	0.008658	68.561	< 2e-16	***
log(FTpple) -	0.017590	-1.874	0.061132 .	0.032963	
log(TOTpple)	0.112189	0.021511	5.215	2.08e-07	***
log(FTwageCAD)	0.750385	0.078179	9.598	< 2e-16	***
log(newRT)	-0.011886	0.004780	-2.487	0.013002	*
log(AreaBurn.ha)	0.051302	0.004535	11.314	< 2e-16	***
log(FWI)	0.073207	0.024768	2.956	0.003167	**
log(ISI)	-0.065984	0.024900	-2.650	0.008131	**

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.2411 on 1549 degrees of freedom
(48784 observations deleted due to missingness)
Multiple R-squared: 0.9798, Adjusted R-squared: 0.9796
F-statistic: 3275 on 23 and 1549 DF, p-value: < 2.2e-16

Verifying assumptions



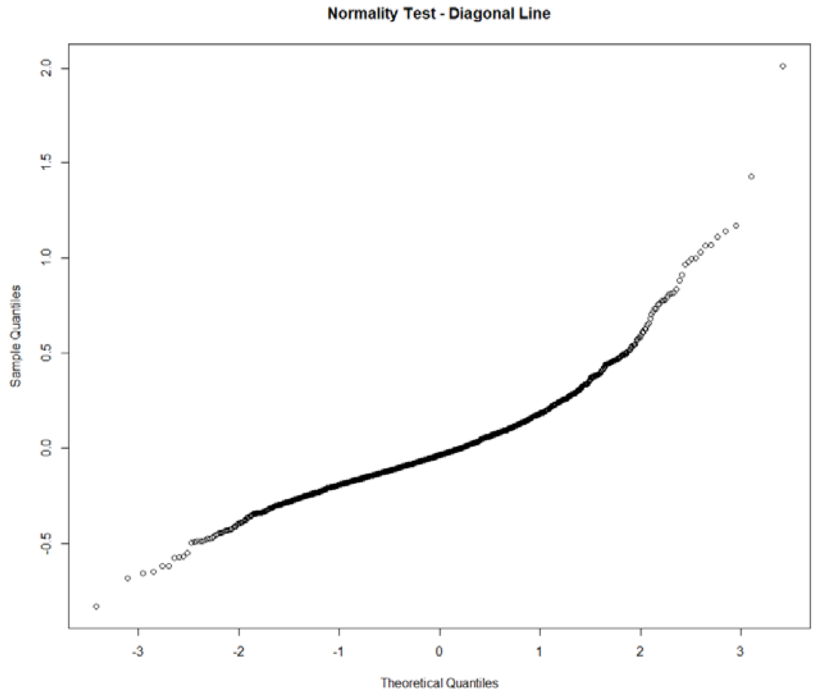


Figure 23. Suppression cost assumptions for the linear analysis were verified for linearity, homoscedasticity, and normality tests using residual graphs.

Suppression efficiency – cost per area burned

Including area burned, but excluding suppression cost as independent variables.

glmulti.analysis

Method: g / Fitting: lm / IC used: aic
Level: 1 / Marginality: FALSE
From 100 models:
Best IC: 13.8693042628914

Best model:

[1] "log(CAD.AreaBurn.ha) ~ 1 + Country + BioClimateZone + log(newMH) + "
[2] "   log(PTppl.hr) + log(FireFlightHr) + log(FTpple) + log(TOTpple) + "
[3] "   log(FTwageCAD) + log(newRT) + log(newIT) + log(AreaBurn.ha) + "
[4] "   log(LandArea.ha) + log(FWI) + log(ISI)"

Evidence weight: 0.0995600236419051
Worst IC: 168.050769620591
15 models within 2 IC units.
15 models to reach 95% of evidence weight.
Convergence after 790 generations.
Time elapsed: 1.45723324219386 minutes.

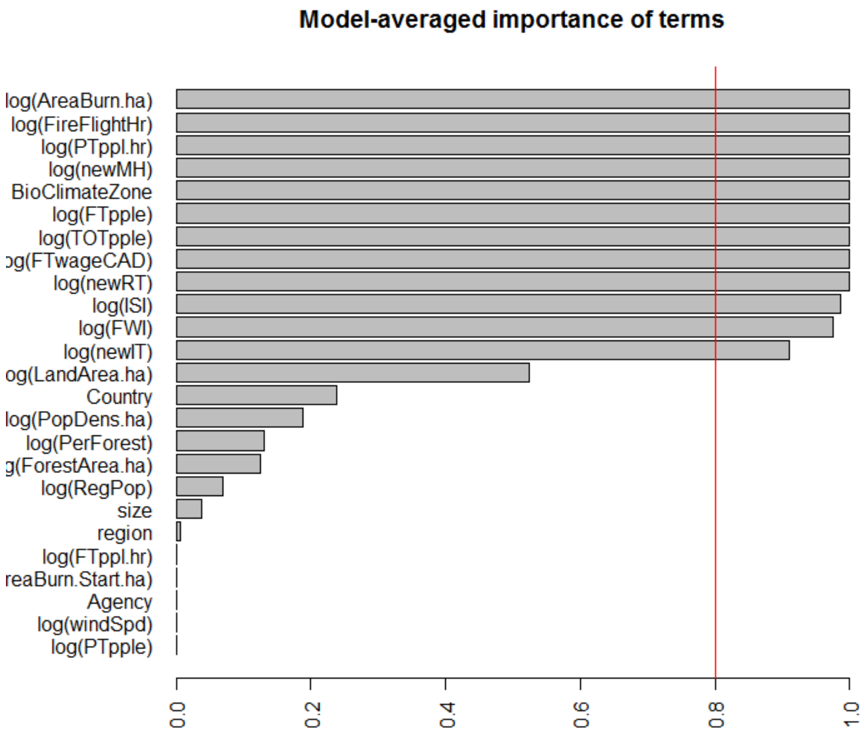


Figure 24. The importance of different variables on the suppression-efficiency model results.

Revised best model summary

Excluding total forest area in the region, country, total land area in the region, and total incident time.

$R^2 = 98.26\%$, $p<0.001$, AIC = 14.73193

```
lm(formula = log(CAD.AreaBurn.ha) ~ 1 + BioClimateZone + log(newMH) +
    log(PTppl.hr) + log(FireFlightHr) + log(FTpple) + log(TOTpple) +
    log(FTwageCAD) + log(newRT) + log(AreaBurn.ha) + log(FWI) +
    log(ISI), data = BothFires)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.82802	-0.14193	-0.03373	0.09837	2.01065

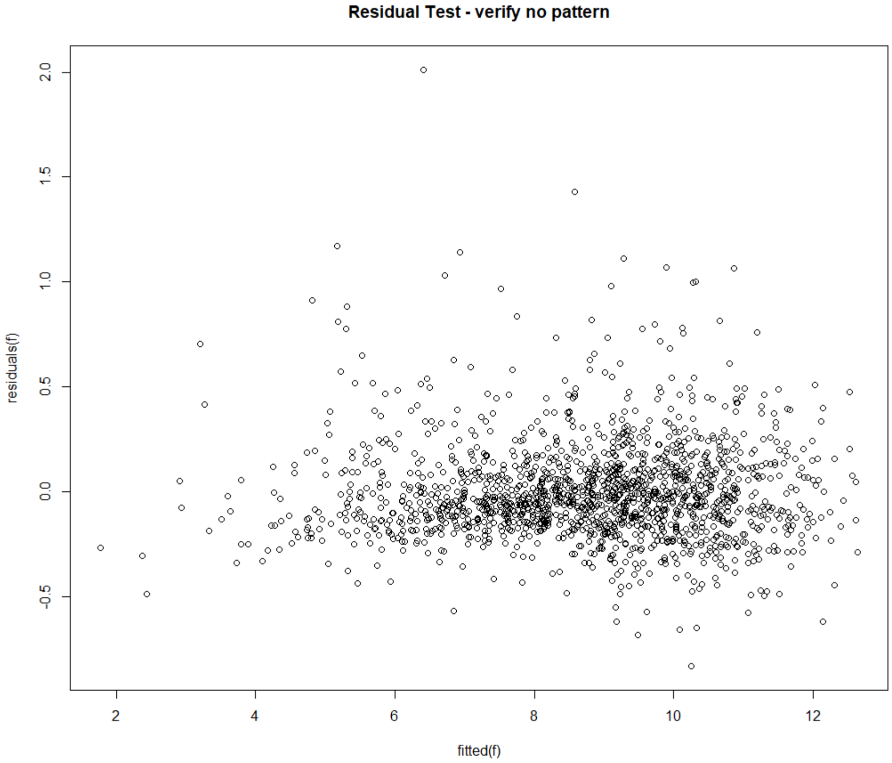
Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	4.811335	0.253089	19.010	< 2e-16	***
BioClimateZone2E	0.407497	0.114786	3.550	0.000397	***
BioClimateZone2W	-0.067235	0.076607	-0.878	0.380259	
BioClimateZone3E	0.306876	0.070385	4.360	1.39e-05	***
BioClimateZone3W	-0.074674	0.063416	-1.178	0.239168	
BioClimateZone4E	0.109428	0.074540	1.468	0.142297	
BioClimateZone4W	-0.076987	0.064634	-1.191	0.233790	
BioClimateZone5E	0.102452	0.070549	1.452	0.146647	
BioClimateZone5W	-0.054532	0.061684	-0.884	0.376797	
BioClimateZone6E	-0.022767	0.062931	-0.362	0.717566	
BioClimateZone6W	-0.018495	0.061593	-0.300	0.764002	
BioClimateZoneN	-0.598061	0.065790	-9.090	< 2e-16	***
BioClimateZoneSE	-0.569978	0.069564	-8.194	5.25e-16	***
BioClimateZoneSW	-0.613392	0.068639	-8.936	< 2e-16	***
log(newMH)	0.295586	0.016513	17.900	< 2e-16	***
log(PTppl.hr)	-0.008222	0.010222	-0.804	0.421301	
log(FireFlightHr)	0.593603	0.008658	68.561	< 2e-16	***
log(FTpple)	-0.032963	0.017590	-1.874	0.061132 .	
log(TOTpple)	0.112189	0.021511	5.215	2.08e-07	***
log(FTwageCAD)	0.750385	0.078179	9.598	< 2e-16	***
log(newRT)	-0.011886	0.004780	-2.487	0.013002	*
log(AreaBurn.ha)	-0.948698	0.004535	-209.214	< 2e-16	***
log(FWI)	0.073207	0.024768	2.956	0.003167	**
log(ISI)	-0.065984	0.024900	-2.650	0.008131	**

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.2411 on 1549 degrees of freedom
  (48784 observations deleted due to missingness)
Multiple R-squared: 0.9829,	Adjusted R-squared: 0.9826
F-statistic: 3866 on 23 and 1549 DF, p-value: < 2.2e-16

Verifying assumptions



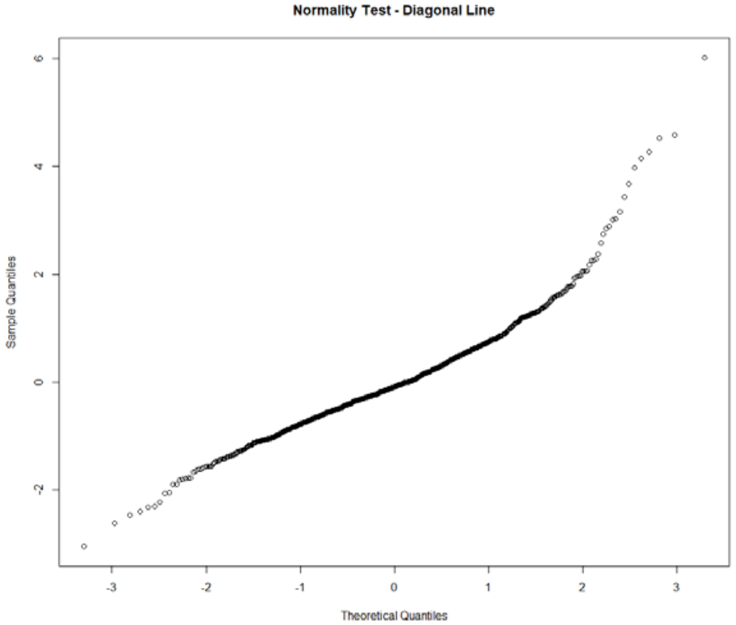


Figure 25. Suppression efficiency assumptions for the linear analysis were verified for linearity, homoscedasticity, and normality tests using residual graphs.