Field evaluation of two image-based wildland fire detection systems.

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Abstract Rapid detection of fire outbreaks is a critical component of fire management because suppression activities are most effective when fires are small. One method of fire detection and location is computer analysis of images from sensors mounted on towers. In this paper we report on a trial of two image-based detection systems under operational conditions in forests in south-eastern Australia. The systems were deployed for 3 months in autumn, 2010 during which time a mix of private, operational and experimental ignitions were undertaken and one unplanned wildfire occurred. A total of 12 experimental fires, 31 planned fires lit by public land management agencies, approximately 250 planned fires lit by private individuals, and 1 unplanned fire were recorded. Both image-based systems were able to detect and locate fires. They performed well for larger planned fires but poorly for small fires (< 1 ha area) at moderate distances (10–20 km). System performance was compared to a human observer for a subset of fires. For these fires the human observer had a higher detection rate and shorter reporting time than the image-based systems. All methods
of detection had a similar level of error for locating fires in the landscape once they had been detected. Operator skill was an important factor in the performance of all systems.

**Keywords** Fire detection · forest · camera · field evaluation

1 Introduction

Wildfires, or bushfires, are a major concern around the world, resulting in significant economic, ecological and social costs each year to infrastructure, ecosystems, lives and property. The earlier the outbreak of a fire is detected, the smaller it will be when the initial attack response arrives and therefore the greater the potential for the initial attack to be successful[1,2]. That is, the early detection of wildfires is critical to the success of subsequent actions to suppress them[3].

One method which can be used to detect and report fires is computer analysis of images obtained from either visual or infra-red sensors. Fire detection using image analysis has been an active area of research in recent years[4–10] and several commercial systems using these methods have been developed. Field studies to test detection systems have been performed in Canada[11], Greece[12], and Turkey[6,7].

These systems use “supervised detection” to report fires. That is, a human operator is required to assess images and alerts from the camera system to determine whether a fire has been observed and needs to be reported. So the potential for human error is inherent in the systems. Assessment of detection by human tower observers in Portugal found that atmospheric conditions[13], topographic roughness[13] and tower location[14] also affect likelihood of detection. Thus, the success of an image-based detection systems in operational use depends not only on the performance of the detection algorithms but also on the design of the detection network and the skill of the human operators.

This paper presents the results of a field trial of two image-based systems in southeastern Australia during March–May, 2010. The aim of the trial was to measure the performance of the systems in an operational context. The detection systems were assessed on their ability to detect and report fires to fire managers, and on the speed and accuracy of the reports. For a subset of fires the performance of image-based detection was benchmarked against a trained and experienced human tower observer.

This work was part of a project sponsored by the Australian Commonwealth Attorney General’s Department to consider the feasibility of image base detection systems [15].

2 Methods

2.1 Experimental layout

Two locations were used in the field trail: the Otway ranges in Victoria and near Tumut, New South Wales (NSW). The Otway ranges (Fig. 1) is a mix of native forest and private agricultural land in moderately complex topography located on the south-western coast of Victoria. Five fire towers oversee this region. The location near Tumut (see Fig. 2) is primarily softwood plantation, with some native forest, surrounded by private agricultural lands in undulating topography on the western slopes of the Great Dividing Ranges. One fire tower at Mt Tumorrama oversees this region. The trial was conducted in autumn, running from March 16th to May 9th, 2010. Operational constraints prevented the commencement of the trial during the peak fire season in summer.
Fig. 1: Location of fire towers and fires in the Otway region of Victoria.

Fig. 2: Location of fires near Tumut, NSW. The fire tower is located at 148°30'E, 35°15'S. Ranging circles are at 5 km intervals. Named localities are sites of experimental fires.
2.2 Weather observations

Daily weather records were obtained from the Commonwealth Bureau of Meteorology for stations in the trial areas: Gundagai in NSW, 45 km north-west of Mt Tumorrama, and Mt Gellibrand in Victoria (Fig. 1). Records included daily rainfall to 9 am, minimum and maximum temperature, 3pm relative humidity, and 3 pm wind speed covering the period 1st May, 2009 to 9th May, 2010. Keetch-Byram drought index (KBDI, a measure of seasonal rainfall deficit [16]) and drought factor (DF, a measure of fuel dryness[17]) were calculated using a computer algorithm adapted from Bureau of Meteorology methods (K. Finkele1, pers. comm.).

2.3 Fires

2.3.1 Experimental fires

Three sites were established for experimental fireing in forests: two in native eucalypt forest at Bungongo and Barnetts Rd, and a third in pine forest at Red Hill (Fig. 2). At each site existing roads and additional bulldozer lines were used to establish plots of approximately 100 x 100 m (1 ha area). Three fires were conducted at the Bungongo site, two at Barnetts Rd, and one at Red Hill. For each fire, conditions driving the fire were measured:

- Local weather conditions using a 2-m automatic weather station,
- Fuel structure by visual assessment[18,19],
- Fuel moisture content by oven drying[20].

Fire spread was measured using metal tags dropped at the fire edge at regular intervals which were later mapped using differential GPS. Smoke characteristics were recorded as visual assessments of colour, density, plume extent, angle of rise, and direction. A video recording of the smoke was also made. Fires were ignited as point fires, to simulate ignition by lightning or arson, and allowed to fire freely with the plot.

A further six stationary fires were conducted (Fig. 2). These consisted of four ignitions of one or two windrows2—in contrast to the operational burning for which many windrows were ignited simultaneously across large areas— and two patches of dead blackberries (80 m−2 and 760 m−2). Two of the windrows were ignited at night to examine the night vision ability of the fire detection systems.

2.3.2 Land management agency fires

During the trial period Forests NSW conducted a program of windrow burning to prepare harvested pine plantation compartments for a new crop. These fires generated multiple small smoke plumes over the area of the fire. 12 distinct fires were conducted during the trial(Fig. 2). Because some of the plantation compartments were in close proximity to one another and may not have been easily distinguished by system operators ignitions on the same day were considered at the locations were treated as a single fire.

Four broadacre prescribed fires were ignited within view of the Mt Tumorrama tower (Fig. 2), while in Victoria 15 fires were conducted (Fig. 1). fires ranged in size from 5

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1 Dr. Klara Finkele, Research Scientist, Bureau of Meteorology.
2 Logging debris piled into rows.
to 1075 ha, and were ignited by aerial incendiary method or from the roadside using drip torches. All fires were in eucalyptus forest and most burned for several days. Some fires were partially extinguished by rain and subsequently reignited. One wildfire was reported in Victoria during the trial, an 84 ha fire at Yeodene (Fig. 1). No wildfires were reported in NSW.

Brief fire behaviour record sheets were provided to agencies to record information about prescribed fires and wildfires during the trial period. For windrow burning Forests NSW also provided maps showing time and location of forest compartments that were burned. GIS shape files of fire area were provided for fires in Victoria. By standard operating procedure, notification of burning operations is available to the public in Victoria and NSW. We did not prevent the operators of the fire detection systems from accessing this information.

2.3.3 Private fires

The majority of private fires were farmers burning stubble, although there were a number of smaller fires (e.g. bonfires, rubbish fires). Formal records of private fires were not available, however several sources of information were used to validate fire detection reports. Copies of burning permits were obtained from local councils and the Victorian Country Fire Authority. These covered only some of the private burning because permit season ended midway through the trial. The issuing of a permit did not guarantee that a fire was lit, so permits were only used for validation. Tower observer radio logs were obtained from three towers in Victoria: Peters Hill, Mt Cowley, and Crowes Lookout. These towers were operating as normal and this meant that less detailed records of observations of fires were kept: in some cases the operator noted the location and nature of a fire, for others only a bearing was recorded, particularly during times of very active private burning. Also, as per normal practice, tower operators were notified before agency prescribed fires were lit, so tower observations were not compared to the trial systems and the tower records were used only to validate reports.

2.4 Fire detection and reporting

2.4.1 Image based fire detection

Two image based fire detection systems were used: FireWatch$^3$ and Forest Watch$^4$. The FireWatch system uses images from a monochrome broadband sensor to detect fires, which are located in the landscape by triangulation using two sensors or from the location of the smoke within one image if only one sensor is available. The Forest Watch system uses colour images from a CCTV camera to detect fires, which are located from smoke position in the images. Both systems use a digital elevation model to assist in determining smoke location. These systems were used because local companies were able to supply equipment and operators within the time constraints of the project. The use of these particular products is not an endorsement.

Both systems used supervised detection methods: computer detection algorithms generated alerts from image data which were validated by human operators before sending a detection report. For the experimental burning phase of the experiment in NSW a human

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$^3$ Manufactured by IQ Wireless, Berlin, Germany. Operated by FireWatch Australia, Sydney, Australia.

$^4$ Manufactured by Envirovision Systems, Durban, South Africa. Operated by Fire Fighting Technologies International, Brookvale, Australia.
observer located on the same tower as the detection systems provided fire reports. Operational constraints did not permit use of human observations at other times and locations.

In NSW one sensor from each of the companies was installed on the Mt Tumorrama fire tower. An additional FireWatch sensor was installed on nearby Compass Hill to provide detection locations by triangulation. Detections made only by the Compass Hill sensor were not used. Where a fire was detected by both sensors, the detection time from the Mt Tumorrama sensor was used. In Victoria, one sensor from each company was installed on the fire towers at Mt Porndon, Crowes Lookout, Mt Cowley, and Peters Hill (Fig. 1). Second FireWatch and Forest Watch sensors were installed on Mt Cowley because it was not possible to locate a single sensor without excessive obstruction due to other sensors and poles on the tower.

FireWatch established a control centre in Burwood, Victoria. This centre hosted two workstations—one each for NSW and Victoria sensors—and a manager’s overview display wall. It was staffed 24 h a day during the trial period from March 3rd to May 9th. A workstation was also installed in the Tumut fire control room and was operated by FireWatch staff during the research burning period (March 15th–26th, 2010). Forest Watch established a control room in Sydney, NSW. This centre hosted two workstations, one each for NSW and Victoria cameras. The cameras were monitored from the start of the trial until the end of the research burning (March 3rd–26th), and from April 6th until the end of the trial. Both systems were operated by staff who had been trained to use the systems but did not have previous experience in fire fighting or fire observation.

2.4.2 Tower Observer

The Mt Tumorrama tower was staffed by an experienced tower operator during the period March 16th to 26th from 9:00 to approximately 17:00 each day. The tower operator kept detailed notes on all smoke sightings including: bearing and distance to smoke, fire type, geographic area or nearby road, a photograph of the smoke. Sightings were communicated to the Forests NSW fire control room in Tumut via telephone. This differed from the usual practice of using radio, to avoid alerting computer operators in the fire control room to smoke sightings. To avoid alerting the tower operator to burning, fire crews did not make a radio call prior to ignition. On March 18th, 22nd and 26th, a researcher was stationed in the tower to observe and validate the tower operator’s observations. The researcher did not provide any information or feedback to the tower operator on research burning plans or operations.

2.4.3 Data collection

Operational constraints meant that none of the detection systems were integrated into normal fire management processes. In NSW, fire detection alerts were sent by email and simple messaging system (SMS) message to the district fire manager. In Victoria, detections were notified by telephone call to the fire control centre, followed up with an email report. At the end of the trial fire detection information was collected from all participants:

– The Mt Tumorrama tower operator provided us with a typed record of smoke sightings and photographs taken. Electronic copies of photographs were also provided.
– FireWatch provided a spreadsheet summarising detections, and for each detection an electronic document with detection data, a map, and one or more sensor images.
- Forest Watch provided a spreadsheet summarising detections, and for each detection two still images and a map. For selected detections a longer sequence of still images was also provided.

2.5 Data analysis

ARC Map software was used to plot the locations of all experimental and agency fires, and the locations given in detection reports for the fire detection systems. Bearing-distance pairs from the Mt Tumorrama tower observer were converted to latitude-longitude pairs for plotting. Detection performance for agency and experimental fires was then assessed against four criteria:

1. Whether a fire was reported or missed,
2. The accuracy of the location given,
3. The time taken to report the fire,
4. The number of false alarms reported.

ARC Map was used to manually match detection reports with fires, with ancillary information in detection reports and fire records such as photographs and addresses used to confirm matches. Location accuracy was measured using ARC Map, while time to detection was calculated from the detection report and fire records. Detection times from reports were used in preference to the time that alerts were received by fire control rooms because the SMS system used does not guarantee message delivery and some cases of delayed delivery were recorded in preliminary examination of the data. False alarms were defined as detection reports which were within a fire permit period, but which could not be matched with a fire permit, agency, or experimental fire. Identification of false alarms outside of permit periods was limited to examination of the images included in the detection reports.

Prior to completion of the data analysis, FireWatch and Forest Watch were provided with a list of the times and locations of fires to allow identification of any sites which were not visible due to obstructions on the mounting towers. The Red Hill site in NSW was partially obscured for Forest Watch, while FireWatch reported some problems with sun-glare for sites to the north-east of Mt Tumorrama in the late afternoon and one site close to Mt Tumorrama tower which was below the field of view of the sensor. The impact of these obstructions is noted where relevant in the results.

For private burning, accurate information was not available on the location or time of ignition of fires so a complete analysis of detection performance was not possible. Instead, after excluding false alarms, the number of fires detected was tallied for each system, with a higher reporting rate indicating better performance. Reported fire locations were plotted in ARC Map. These were used along with images to match FireWatch and ForestWatch reports in order to determine which fires were reported by both systems.

3 Results

3.1 Weather conditions

Rainfall in the 12 months to the start of the trial was average or slightly above average for both the NSW and Victorian study areas. Rain over south-eastern Australia during late summer and in the first week of March was sufficient to drop the KBDI close to zero at
the beginning of the trial. This indicated very wet conditions and normally does not happen until winter, and the KBDI remained below 50 for the duration of the trial most of the trial area in NSW and below 100 in Victoria. From a seasonal perspective, the entire trial was conducted in mild, autumn conditions; temperatures and humidity in March were moderate, with maximum temperatures ranging 21.5–32.1 °C, and humidity only as low as 24%. Wind speeds were very low due to the presence of large high pressure systems over south-eastern Australia for much of the trial; 3 pm wind speeds were less than 10 km h⁻¹ for most of the trial period. These conditions made research burning difficult but offered many opportunities for prescribed burning.

3.2 fire characteristics

3.2.1 Experimental forest fires

Experimental fires in eucalypt forest spread successfully while the fire lit in pine forest was self-extinguishing after 15 minutes. While the conditions during the actual research fires
were marginal, with rates of spread of 0.4–0.8 m min\(^{-1}\) and flame heights mostly below 1 m, there was considerable smoke for detection (Fig. 4). The time of observation of the smoke first appearing above the forest canopy varied from 2 to 20 minutes after ignition and was white or grey in colour with a plume angle of 60–90 degrees. Most of the smoke came from the smouldering combustion of the coarser woody material behind the flame front. In most cases the smoke plume did not rise above the horizon (Fig. 4).

Fig. 5 shows the cumulative distance travelled by the head fire and area burnt for the individual fires. The rate of fire growth (i.e. increase in area burnt) ranged from 1.8 to 39.3 m\(^2\) min\(^{-1}\). The variation in the growth rates was due to many factors: dead fuel moisture content, surface fuel distribution, combustion rate, burn-out time of fuels, local winds in the flame zone and atmospheric stability. The mild burning conditions and slow fire development was reflective of the high fuel moisture and mild weather conditions at the time of the experiments.

### 3.2.2 Other fires

Many windrows were ignited at each location, generating multiple small smoke plumes over the area of the fire and generating a large amount of white or grey smoke (Fig. 4). The windrows burnt for several days, creating widespread haze during calm conditions, particularly in the early morning.
3.3 Fire reporting

All six fires in forest fuels were seen by the tower observer within 30 minutes at a size of less than 200 m$^{-2}$ (Fig. 5). FireWatch was the only camera system to report any of the experimental forest fires, although detection was later than the tower operator by 35 minutes and the fire was five times larger at detection (Fig. 5). None of the detection systems reported the small and short lived blackberry fires. Performance for windrow and prescribed fires was better, with all systems reporting most of these fires in NSW and Victoria (Table 1). Note however that information on the location and planned ignition date was publicly available for prescribed burning in Victoria.

The two image-based systems successfully reported the two night-time windrow ignitions. A number of night-time updates on already burning windrows and prescribed fires were also included in data sets, indicating that the night vision capabilities of both systems worked during the trial. There was not enough information to gauge relative performance at night. The tower was unoccupied at night and so the night-time ignitions were not reported until the following morning.

The four prescribed fires in NSW and 15 in Victoria were all considerably larger (5–1075 ha) than the experimental fires (0–1 ha) and because they used drip-torch lines or aerial ignition rapidly produced a large amount of white or grey smoke (Fig. 4).

The majority of private fires were stubble fires, varying in size up to a few hectares. They are usually lit from the edge of a paddock, producing a large plume of smoke for a short period of time (Fig. 4), up to several hours.

Experimental burning of single windrows produced a thin column of smoke, similar to those from the operational windrow fires but smaller in extent and lasting for 1–2 days. The blackberry fires lasted a very short time, less than 30 mins, and produced a small column of very thick, black smoke.
Table 1: Summary of fire detection reports. Numbers in brackets indicate the number of fires that should have been visible to a particular detection system in cases some could not be detected due to obstructions or lack of operators.

<table>
<thead>
<tr>
<th>fire type</th>
<th>Number of fires</th>
<th>Number of reports</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tower</td>
<td>FireWatch</td>
</tr>
<tr>
<td>Experimental forest fire</td>
<td>6</td>
<td>9 (10)</td>
</tr>
<tr>
<td>Windrows–daytime</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>Blackberries</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Prescribed fires–NSW</td>
<td>4</td>
<td>3 (3)</td>
</tr>
<tr>
<td>Prescribed fires–VIC</td>
<td>15</td>
<td>NA</td>
</tr>
<tr>
<td>Wildfire–VIC</td>
<td>1</td>
<td>NA</td>
</tr>
<tr>
<td>NSW Private burning (16–26 March)</td>
<td>Unknown</td>
<td>45</td>
</tr>
<tr>
<td>NSW Private burning (6 April–9 May)</td>
<td>Unknown</td>
<td>NA</td>
</tr>
<tr>
<td>VIC Private burning (6 April–9 May)</td>
<td>Unknown</td>
<td>NA</td>
</tr>
</tbody>
</table>

Almost all the private fires in NSW that were reported by the tower were missed by the image-based systems (Table 1). Many of these fires were on agricultural land over 40 km from the tower, well outside the normal operating range of the detection systems. FireWatch reported 35–40% more private fires than ForestWatch over the course of the trial. However, only 10% of private fires were reported by both systems, meaning that most fires reported by one system were missed by the other.

The human operators did an excellent job of dismissing computer generated alerts which would have been false alarms. One report was received from FireWatch that was located on Forest NSW tenure but could not be validated against records. It may have been a false alarm or a mislocated small private fire. No false alarms were received from Forest Watch.

After the completion of the trial, FireWatch re-analysed detection data using information on locations and ignition times for experimental and operational fires. In this exercise, 8 of 14 unreported ignitions were associated with computer alerts which were dismissed by operators. It is not possible to determine from this reanalysis whether alerts were dismissed due to operator inexperience or due to limitations of viewing the landscape as a 2-dimensional grey-scale image.

### 3.4 Speed and accuracy of detection

Fig. 6 shows detection time and location error aggregated across experimental, windrow and prescribed fires for each detection system. Private burns were not included as ignition times and accurate locations were not known. Detection times for the tower operator were shorter than for the image-based systems. Median reporting time for the tower was 15 minutes, with 75% reported within 44 minutes. For FireWatch these times were 39 and 141 minutes, and for Forest Watch 46 and 123 minutes. Median detection times for the image-based systems were significantly higher than the tower ($p < 0.05$, Wilcoxon rank-sum test[21]). The tower operator was less accurate at locating fire in the landscape with median error of 600 m, compared to 400 m for both FireWatch and Forest Watch. Medians were not significantly different. Several large location errors were reported by both image-based systems, up to 18 km in one case. Examination of images indicates that these were due to topographic shad-
owing[14] or incorrect identification of the base of the smoke. Where it was used, location by triangulation using two sensors was most accurate, with errors < 200 m and no large errors.

4 Discussion

The two image-based fire detection systems performed less well at detecting fires than the human observer. These systems reported a lower proportion of fires and took longer to detect those fires that were reported. The low rate of detection for small research fires was of particular concern, given the need to detect fires quickly if they are to be suppressed by initial attack[1]. It is likely that if the research fires had been allowed to burn freely through the landscape they would eventually have been detected, although one of the fires was allowed to burn an entire 1 ha plot but was not reported by either system. Detection performance was better for prescribed fires in NSW and Victoria, but these were large fires which, had they been wildfires of the same size burning under summer conditions would in most cases certainly have been beyond capacity for successful initial attack. Detection of private fires in Victoria and NSW was inconsistent. As many of the fires were at distances beyond the design characteristics of the cameras (approximately 15 km radius) this was not unexpected. False alarms were not a problem for either automatic system during this trial. Human operators of the systems successfully identified all but one possible false positive.

Once fires were detected all camera systems were able to locate the fires with similar accuracy to the human observer in most cases. All systems made some gross errors (4–18 km) caused by targeting locations behind fires. It is likely that more experienced operators with local knowledge would be able to identify and correct for these errors by correlating mapped detection locations with landmarks visible in the detection images.

The experimental design of this project tested each system as a whole, including not just the sensors and algorithms but also the human operators. Reanalysis of FireWatch data indicated that some fires were missed because the operators did not consider computer generated alerts to be real fires. This highlights the importance of using skilled operators.

Fig. 6: Left) Time taken to report fires for each detection system. Right) Location error. Horizontal lines are the median value, boxes are 25% to 75% inter-quartile range, whiskers are up to 1.5 times inter-quartile range.
the other hand, it is possible that the limitation of viewing the landscape through a camera was a greater constraint in correctly identifying smoke than operator experience.

Detection performance was at least partly a function of fire size and distance from the camera. Large prescribed fires were detected at long distances (up to 70 km) while smaller fires at moderate distances (10–20 km) were missed. Any statements about camera effectiveness at a particular distance need to be qualified by the size of fire that can be detected.

It is possible that in summer conditions, where point ignition fires would grow more rapidly than our experimental fires and produce smoke with different characteristics, the detection systems might perform differently when detecting small fires. On the other hand, atmospheric haze and raised dust might hinder detection. It is also possible that the detection algorithms used to process camera images would benefit from adaptation and calibration to Australian conditions. For example atmospheric conditions, landscape appearance, and smoke characteristics all differ from other parts of the world.

5 Conclusions

The two image-based systems tested were able to observe and locate fires during both day and night. However, detection by these systems was slower and less reliable than by a trained human observer. Both sensor types tested (monochrome and colour with night mode) were suitable for detection during day and night. Under trial conditions, the FireWatch system performed better than Forest Watch at supervised automatic detection but both were outperformed by the human observer during the day. Different results might be obtained in summer conditions.

Both image-based systems could adequately locate fires once they were identified, with a similar level of error to the human observer. Single sensor location worked well when the base of the smoke was identified correctly, and introduced errors when the base of the smoke column was misidentified in an image or hidden behind a hill. Both systems provide tools to allow a skilled operator to identify and correct these errors. Location by triangulation was the most accurate method.

The human observer is an integral part of all detection systems. Skilled operators are required to decide whether computer generated alerts are fires or false alarms, and to validate fire locations against known landmarks.

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References


