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# Allocating fuel breaks to optimally protect structures in the wildland–urban interface

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**Abstract.** Wildland fire is a major concern in the wildland–urban interface (WUI), where human structures intermingle with wildland vegetation. Reducing wildfire risk in the WUI is more complicated than in wildland areas, owing to interactions between spatial patterns of housing and wildland fuels. Fuel treatments are commonly applied in wildlands surrounding WUI communities. Protecting the immediate surroundings of structures and building with fire-resistant materials might be more effective, but limited resources and uncooperative homeowners often make these impractical. Our question was how to allocate fuel treatments in the WUI under these constraints. We developed an approach to allocate fuel breaks around individual or groups of structures to minimise total treatment area. Treatment units were ranked according to their housing density and fire risk. We tested this method in a Wisconsin landscape containing 3768 structures, and found that our treatment approach required considerably less area than alternatives (588 *v.* 1050 ha required to protect every structure independently). Our method may serve as a baseline for planning fuel treatments in WUI areas where it is impractical to protect every single house, or when fire-proofing is unfeasible. This approach is especially suitable in regions where spotting is a minor cause of home ignitions.

## Introduction

Each year, a large number of communities and structures are exposed to wildfire, especially in areas where human settlements intermingle with wildland vegetation, defined as the wildland–urban interface (WUI; Radeloff *et al.* 2005). In recent decades, there has been an increase in housing growth in the WUI in the continental United States, and this trend is projected to continue in the future (Nowak and Walton 2005; Hammer *et al.* 2007). The WUI is defined as the area where houses and wildland vegetation are either adjacent (interface) or intermingled (intermix) (Radeloff *et al.* 2005). Wildfire is a significant risk in the WUI, both to housing units (owing to wildfire spread through wildland fuels), and to wildland vegetation (owing to human-caused ignitions that are frequent near human structures) (Sturtevant and Cleland 2007; Syphard *et al.* 2007).

Extensive research has been conducted to devise methods to decrease wildfire risk, but only few methods are specifically designed for the WUI. Suggested methods focus primarily on fuel treatments that are intended to limit fire spread and overall size, decrease its severity, and protect landscape values (Reinhardt *et al.* 2008). The questions underlying prior studies thus were where, when, and what type of fuel-management actions should be implemented in order to minimise fire risk. At the scale of individual houses, Cohen (2001) defined the 'Home Ignition Zone' (HIZ), which represents the house itself and its immediate surroundings. Under the HIZ and other parcel-scale approaches, individual homeowners make their properties better adapted to fire, minimising risk by building with fire-resistant materials (to prevent ignition from fire brands), and managing the vegetation in the immediate surroundings of the house (to limit ignition from surface fires) (Cohen 2000). However, the HIZ concept requires homeowners to cooperate, and managers of public lands are faced with the task of how to protect structures from wildfire via management actions on public lands.

For purposes of discussing methods to reduce fire risk through fuel management, it is helpful to classify land into three zones (Arno and Brown 1989): (1) wilderness and natural areas, where human access and exposure to risk are minimal, naturally ignited fires are allowed to burn, and fuel management focusses on reducing fire severity; (2) general forest management zones, which include more accessible forests and forests managed for timber; and (3) residential forests, which border or surround homes, and correspond to both interface and intermix WUI. In the majority of cases, fuel management in residential forests is aimed at protecting communities, infrastructure, and homes. Zones 2–3 can be further divided into three risk-reduction units (Bevers *et al.* 2004): individual structures and their immediate surroundings; the boundaries between a community (or a cluster of structures) and wildland vegetation; and the wildland vegetation between communities.

Despite its importance to management and planning, the question of where fuel treatments should be placed relative to or within these zones remains unanswered, especially regarding

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the placement of fuel treatments in zone 3. Expert opinion-based approaches suggest that fuel treatments should be placed as strips along ridgelines, on upper south and west slopes, along valley bottoms, along roads, and around communities (Quincy Library Group 1990; Agee *et al.* 2000). The stewardship and fireshed assessment (SFA) management approach (Bahro *et al.* 2007) uses a group of experts to develop manual delineation of fuel treatments that are then calibrated by FARSITE (Finney 1998) and FlamMap (Finney 2006), two commonly used fire simulation models. In a different approach, prescribed burns planned by 10 fire experts were used to devise five alternative firebreaks in a provincial park in southern Canada, which were then tested by the Prometheus fire model (Suffling *et al.* 2008).

A variety of other approaches have been used to investigate optimal placement of fuel treatments. For example, Ager *et al.* (2007) simulated the effects of treating all stands in the WUI where tree density exceeds a certain threshold. More complex approaches prioritise subwatersheds for treatment by identifying high-risk areas, defined by a combination of high fire hazard, predicted extreme fire behaviour, and high ignition risk (Hessburg *et al.* 2007). Similarly, elevation, housing density, distance to roads, slope, canopy cover, and fire hazard can function as criteria for fuel-treatment selection (Platt *et al.* 2008). Multiple-objective optimisation procedures can also be used to select polygons for fuel treatments (Kennedy *et al.* 2008). In all of the above methods, a map of candidate units for treatment (polygon, stand, subwatershed) with predefined boundaries is created in advance and methods differ in the way they select units.

Another group of methods makes no prior decision about the boundaries of the treatment units and instead tackles the delineation of treatment units as part of the placement problem. Percolation theory can be used to assess how much area needs to be treated with randomly placed fuel treatments in order to form continuous fuel breaks that will halt potential fire spread (Bevers *et al.* 2004). In another grid-cell-based approach, the locations of fuel treatments are optimised by mixed integer programming, accounting for ignition risk, conditional spread probabilities between adjacent cells, simulated fire intensity values, and values at risk (Wei *et al.* 2008). A purely geometrical approach consists of multiple treatment units that are intended to slow the forward spread of fire while promoting flanking, thus reducing the overall spread rate (Finney 2001). This scheme was tested under three spatial rule sets (treatments placed where higher burn probabilities exist, between natural fire breaks – lakes, and at the boundary of the entire area) to assess the change in fire behaviour and spread in Prince Albert National Park, northern Canada (Parisien *et al.* 2007). An iterative computational method uses major fire flow paths (identified by a minimal travel time algorithm; Finney 2002) as indicators of where fuel treatments should be located (Finney 2007).

The above methods were developed primarily for wildland areas, i.e. zones 1 and 2 in the classification by Arno and Brown (1989). Fuel treatments to protect structures in the WUI – zone 3 – need to function at a much finer spatial scale, and need to take the location of structures into account. In the WUI, the flammability of an individual structure (e.g. roofing material, walls and presence of a wooden deck) plays a pivotal role in its probability of being ignited by wildfire (Cohen and Stratton 2003, 2008; Spyratos *et al.* 2007). In areas where there is extensive spotting, such as the western United States, fire brands are the main cause of home ignitions, and constructing fuel treatments to limit spotting is not feasible; thus, the best way to limit ignitions is to reduce the flammability of the houses. In addition, the distance between the structure and the nearest wildland fuels also affects the structure's ignition probability, due to ignition via radiant heat transfer from a nearby fire. Even an extreme crown fire (flame length of 20 m) can fail to ignite or even scorch a wooden wall that is located only 30 m away (Cohen 2000). Thus, the HIZ approach (Cohen 2001; Reinhardt *et al.* 2008) suggests that using fire-resistant building material and clearing fuels in the immediate surroundings of structures are the only actions needed in order to minimise fire risk in WUI areas (no wildland fuel treatments are necessary).

Although research supports the effectiveness of protecting homes by using fire-resistant materials and managing the vegetation and other flammable materials within the HIZ, not all homeowners will carry out these recommendations. Even where public awareness is high and support for (and enforcement of) zoning regulations is good, not everyone has the resources to reduce the fire risk to their home. Some homeowners lack money, others lack time, and vacant properties are seldom well maintained. Neighbours of those who neglect property maintenance are also affected. Furthermore, the HIZ concept was developed in forests with a high potential for spotting, but fuel treatments in other ecosystems (e.g. grasslands) can be a very effective way to limit fire spread, and thus fire risk to houses.

Therefore, it may be more cost-effective to place fuel treatments so that they protect a large number of houses simultaneously, rather than or in addition to treating the vicinity of each house individually. In our study, we assumed that fuel treatments near WUI homes and communities may be needed for a variety of reasons, and that efficiency in placing fuel treatments is necessary. The question is if in such cases, fuel treatments that aim to reduce fire risk to housing in the WUI should focus on the immediate surroundings of the houses, on the boundaries between communities and wildland vegetation, or on fuels further in the wildland in order to reduce fire risk to structures most effectively.

In the fire-risk terminology, structures in the WUI are landscape values that need to be protected. Fuel management in the WUI is a complex problem, because structures are spread across the landscape in varying spatial configurations that intermix with different fuel types and physical conditions. Houses are, themselves, a source of fuel with different characteristics than that of the surrounding wildland fuelbed (Rehm *et al.* 2002). The spatial pattern of structures is often complex, with various configurations, from clumped (high-density communities), to linear (structures along roads, rivers, or lakes), dispersed (individual or small numbers of structures distant from each other), and any combination of the above. Because it is not always practical to protect each individual house, managers sometimes apply fuel treatments around entire communities (Schmidt *et al.* 2008). When the boundary between the community and the wildland is well defined, locating a community protection fuel treatment is straightforward, but locating fuel treatments is much more complicated when there are multiple spatial configurations of communities and individual structures in the landscape. What would be the best way to delineate a fuel treatment so that all structures will be protected? Which houses should be protected at the individual level and which at the community level? Our goal was to answer these questions, and we developed a spatial allocation approach that generates fuel breaks around all of the structures in a WUI area while minimising total treatment area over the entire landscape. We applied the method in a 60 000 ha WUI area in north-western Wisconsin.

## Methods

### Overview

The spatial allocation of fuel treatments near structures in the WUI is defined here as follows: find a set of linear fuel treatments that surround individual structures or clusters of structures so that all structures in the landscape are protected. The decision of whether to protect single structures or a cluster of structures is based on an objective function that minimises overall treatment area, which is the sum of all fuel treatment areas. For the sake of simplicity, the fuel treatment that we applied was a 30 m-wide firebreak. However, the choice of treatment type has no implication for the allocation algorithm, and any other form of treatment (e.g. shaded fuel breaks, thinning) could be used just as well. We chose a treatment width of 30 m because experiments by Cohen (2000) regarding the ignitability of structures due to heat transfer from a nearby fire suggested that a 30-m buffer was almost always sufficient to prevent structure ignition. Our method does not depend on a specific treatment width though, and another treatment width could be easily substituted.

The allocation algorithm consisted of two steps (Fig. 1): (1) generation of alternative solutions (fuel treatment configurations at varying clustering distances); and (2) selection of the best configurations according to the objective function. The process started with a map of structures (in the format of an *ArcGIS* shapefile) and existing firebreaks, in this case, lakes. The first part of the algorithm was conducted in *ArcGIS*, and the second in *MATLAB*.

### Generation of alternative fuel-treatment configurations

In WUI areas that contain a large number of structures, there are many potential solutions for allocating lines that connect points or clusters of points. We simplified the problem by introducing six pre-defined cluster sizes, based on the distance between neighbouring structures. These were: individual houses, 100, 200, 300, 400, and 500 m. Each of these distances denotes the criteria for lumping two individual structures into a cluster (e.g. if structures were within 100 m of each other, they were treated as a cluster rather than individual houses, and a fuel treatment surrounded them all). In clusters with less than three structures, structures were treated individually and not as a group.

For clusters with three or more structures, the minimal bounding area was generated by finding their minimal convex polygon. A planar polygon is convex if it contains all the line segments connecting any pair of its points (Weisstein 2009); thus it is the polygon with the shortest perimeter that contains a given set of points (Fig. 2). Applying a 30-m buffer around each polygon created a potential treatment unit, but some of these treatment units were suboptimal because they did not capitalise on natural or existing fuel breaks nearby, such as lakeshores (Parisien *et al.* 2007) (Fig. 2). To overcome this problem, we corrected polygons that were within a certain distance from lakeshores in the following manner. We defined a minimum distance of 150 m between a closed polygon and the lakeshore. Clusters that contained structures that were within this distance to lakeshores were expanded towards the lakeshore, and their structures were projected to the shoreline using a minimum distance rule. The 'ghost' structures on the lakeshore and the real structures in their original locations together formed a new convex polygon, which accounted for the existence of the shoreline nearby.

In addition to lakeshores, road networks may also serve as existing fuel breaks, and can in principle be accounted for in the same manner. However, roads vary in their ability to serve as fuel breaks, depending on width and construction material (non-flammable asphalt *v.* dirt that allows some vegetation growth). We did not have sufficient information about the roads in the study area; therefore we did not incorporate them into the analysis. A fuel treatment was delineated by adding a 30-m buffer around each new polygon. The portion of the treatment that was inside the lake was then removed, yielding the final treatment scheme for each size lakeside cluster. A unique code was assigned to each set of treatment units that surrounded a single convex polygon. This process was repeated for the five cluster sizes (100 to 500 m), yielding a set of candidate treatment units (Fig. 3).

For individual structures, the process was simpler. We generated a 30-m buffer around each structure. In cases where these buffers overlapped, they were merged into single treatment units that contained multiple structures (but each structure within them was protected from all directions, in contrast to structures in clusters). Here, too, each unit was given a unique code.

After the six sets of candidate treatments were formed, we created a membership table for each structure (Fig. 4). Each row represented an individual structure, and each column denoted the code of the treatment unit to which the structure belonged in each cluster distance (i.e. there were six columns). In cases where a structure was not part of a treatment unit at a certain cluster distance, the cell was given the value of zero. Owing to the inherent properties of convex polygons, polygons of higher cluster distances fully contained all polygons of lower cluster distances; therefore, the table entities were nested between columns (except where structures were more than 500 m away from any other structure, in which case they were not contained by any convex polygon).

### Selection of the best treatment configuration

For each treatment, at any cluster distance, we calculated the total treatment area (A), which is the total area of the 30-m buffer surrounding that cluster or individual structure. We then developed a recursion heuristic, implemented in *MATLAB*, in order to determine the best configuration of clusters or individual structures that minimised the treatment area over the entire landscape. The algorithm was based on the fact that the convex polygons that surround structures were nested. Therefore, the treatment area surrounding a given polygon P at a large clustering distance was compared with the combined treatment areas of all polygons of a lower clustering distance contained by P, and the treatment combination that had smaller area was chosen. The code consisted of a recursion that operated by moving through the membership table from high cluster distances down to individual structures and back. In each step, the code compared the area of a given treatment unit with the summed area of all

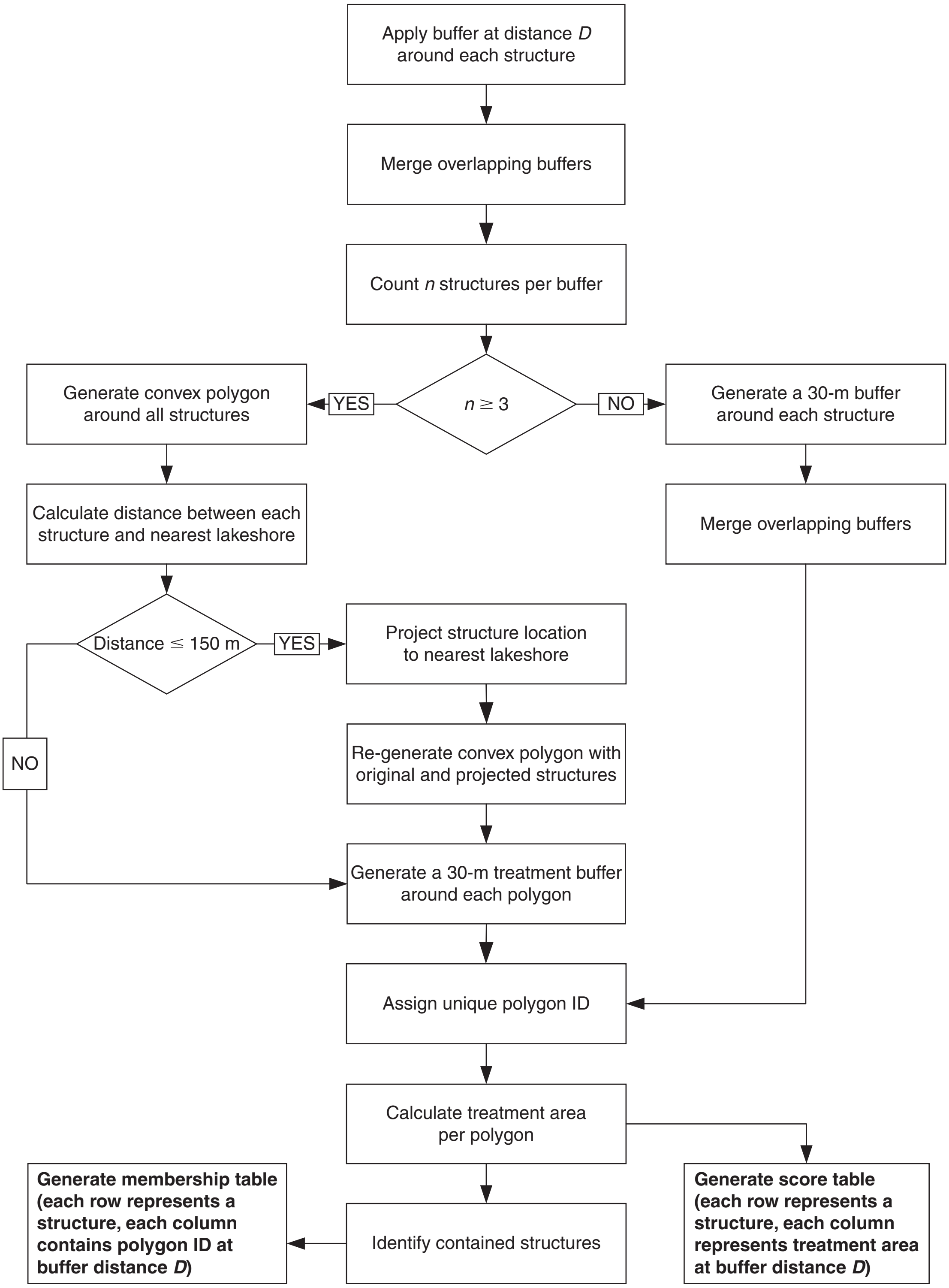


**Fig. 1.** The first part of the delineation algorithm.

treatment units that were contained by it at a lower cluster size and determined which was smaller. The membership table in Fig. 4 exemplified the process:

1. Calculate the area of C1.
2. Calculate the area of B1.
3. Calculate the areas of A1–A4.
4. Compare the area of B1 and the areas of A1–A4. Keep the polygon with the smaller area.
5. Calculate the area of B2.
6. Calculate the areas of A6–A8.
7. Compare the area of B2 and the areas of A6–A8. Keep the polygon with the smaller area.
8. Compare the area of C1 and the outcome of (4) and (7) plus the area of A5. Keep the polygon with the smaller area.

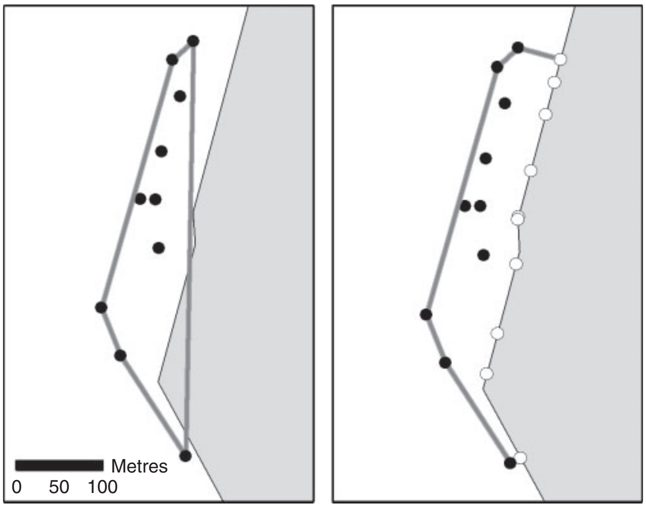


**Fig. 2.** Left – an inefficient delineation of a fuel treatment (dark grey line) around structures near an existing non-fuel area (lake, grey area). Right – its corrected position using projected 'ghost' structures (white circles).

In practice, all area calculations were done in the GIS in advance, so the corresponding treatment area for each code in the table was known. All treatment combinations were enumerated and the entire process took less than 1 min to complete using a Dell server with a 3.6-GHz Intel Xeon processor and 8 GB of RAM. The result of the process was a table in which each structure had a code of a single treatment unit in a certain cluster distance and zero in all other row entities. The table contained the codes of treatment units that minimised the overall treatment area over the entire landscape. The unique values of each column (where column denotes cluster distance) were re-imported into *ArcGIS* and identified in the corresponding fuel treatment layer. They were then copied into a new layer, and all six new layers were merged to yield the final treatment configuration for a given cost function. We compared the area of the optimised result with those of the six initial treatment configurations (non-optimised, clustering distances of 100 to 500 m, and single structures). As all of the treatments except the single structure allocation did not contain all structures (i.e. there were structures more than the clustering distance away from their nearest neighbour), we added the individual structures that were left out for each treatment scheme, and treated these individually.

### Ranking treatment units

Our algorithm assumed that all structures in the landscape had to be treated. In reality, limited resources and time often prevent the application of fuel treatments around all structures. The final step of the process was designed to assist decision-making regarding which treatments should be performed when it is not possible to conduct all of them. In this step, treatment units were ranked according to the following parameters: number of structures protected (maximum is best), and summed fire risk for all structures within the treatment unit (maximum is best). We then assessed the effect of sequentially adding treatment units on overall treatment area and number of structures protected.

We had calculated the fire risk for each structure in a prior study (Bar Massada *et al.* 2009). The fire-risk assessment was

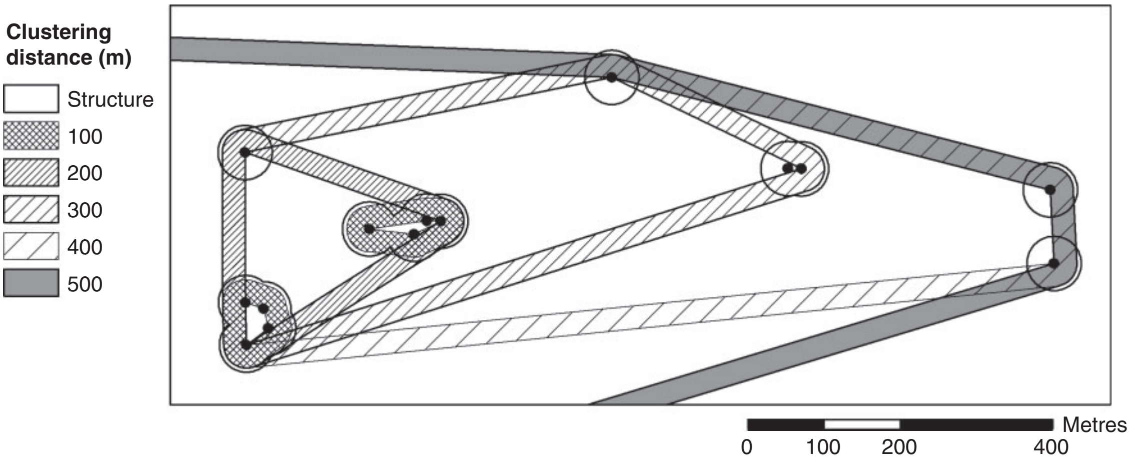


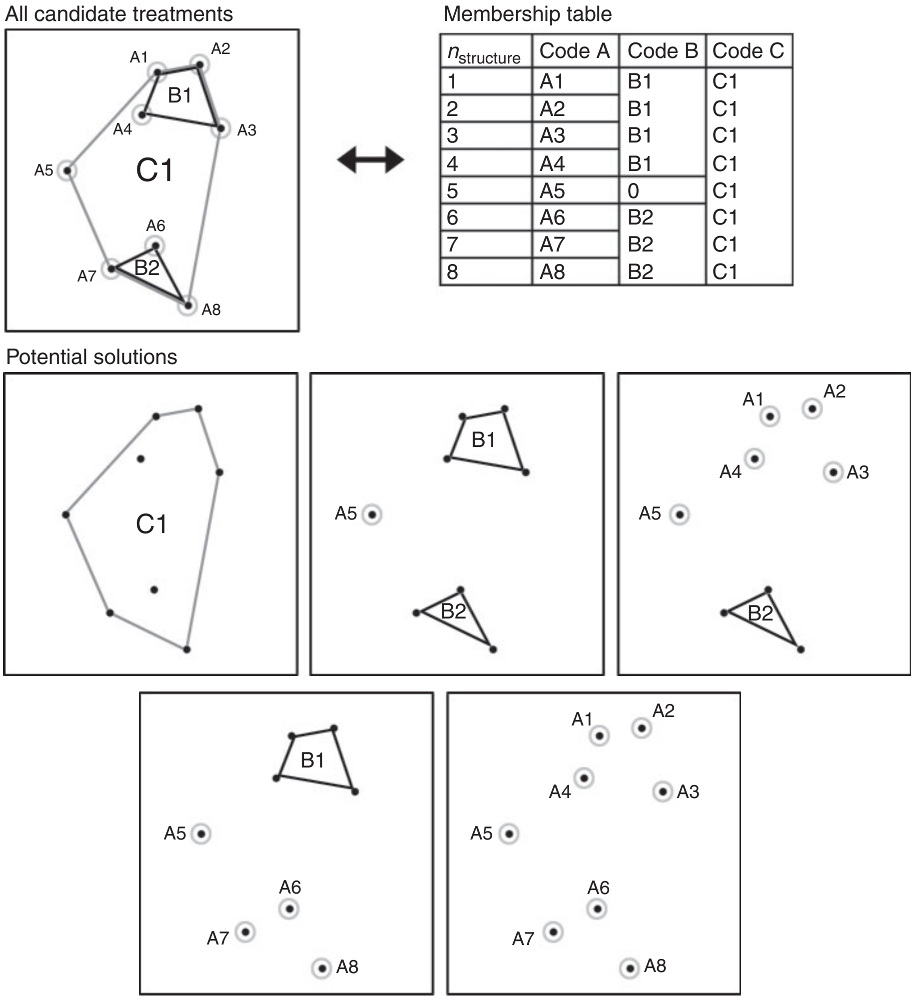
**Fig. 3.** The hierarchical structure of treatments that arises from using minimum convex polygons. Clustering distance indicates the maximum allowed distance between two neighbouring structures that assigns them to the same cluster. Circles around individual structures were exaggerated to enhance visibility.

based on fire-spread simulations using a Minimal Travel Time (MTT) algorithm (Finney 2002), implemented in FlamMap (Finney 2006). In the prior study, we conducted 6000 independent MTT simulations using random ignition locations and extreme (95th percentile) weather conditions, to assess potential fire spread in the study area (Bar Massada *et al.* 2009). The fuel and environmental data required to run MTT was obtained from the LANDFIRE project (Rollins and Frame 2006), and roads (which essentially act like existing fuel breaks in the fire simulations) were added to the fuel map using TIGERLINE road data (http://www.esri.com/data/download/census2000_tigerline/index.html, accessed 18 December 2010). The fire perimeters generated in those simulations were overlaid, summed at the pixel level, and then divided by 6000 to yield a burn probability map. The burn probability map portrayed the number of times a pixel is likely to burn if there are 6000 randomly located ignitions in the study area and weather conditions are extreme (Finney 2005). To calculate burn probabilities for individual structures, all structures in the study area were digitised from aerial photos, and overlaid with the burn probability map. Each structure was then assigned the value of the burn probability map at its corresponding location, representing its fire risk.

## Results

### General

The optimisation approach successfully identified a treatment scheme that had a much smaller overall treatment area than all other alternatives (Fig. 5). The overall optimal treatment area was 541.9 ha (<1% of the total study area) and contained 548 individual treatment units. The largest treatment area within the optimal solution was 71.9 ha, surrounding a chain of lakes in the centre of the study area (Fig. 6). The smallest treatment area was 1.5 ha, surrounding an individual structure on a lakeshore. The treatment units that made up the optimal solution tended to be small (Fig. 7), as the majority of fuel breaks were selected at the scale of individual structures (421 out of 548). Yet, only 535 structures out of a total 3768 (14.19%) were protected at the individual structure level (units at the individual scale may



| $n_{\text{structure}}$ | Code A | Code B | Code C |
|---|---|---|---|
| 1 | A1 | B1 | C1 |
| 2 | A2 | B1 | C1 |
| 3 | A3 | B1 | C1 |
| 4 | A4 | B1 | C1 |
| 5 | A5 | 0 | C1 |
| 6 | A6 | B2 | C1 |
| 7 | A7 | B2 | C1 |
| 8 | A8 | B2 | C1 |

**Fig. 4.** Candidate treatment locations (top left), their corresponding membership table (top right), and five potential treatment allocations (bottom). In this example, there are three nested scales of candidate treatment configurations (around individual structures (A) and at cluster distances B and C).

contain several structures if they are less than 30 m apart). This is because the eight largest units contained 62% of the structures. Larger treatment units tended to appear in the central and northern parts of the study area, which are characterised by large lakes that are almost completely surrounded by structures. Smaller treatment units appeared either near smaller lakes or dispersed and far from lakes.

Protecting every house individually, which represents the maximal protection capability, required an area of 1050.7 ha, i.e. 93.9% more treatment area than in the optimisation approach. Regarding the initial treatment configurations, increased clustering distance tended to decrease the overall treatment area, even when the isolated structures were added. However, the difference between these areas was rather small, 11.1% between the 100- and 500-m distances respectively. Still, the optimised allocation formed a much smaller area than the best initial configuration – 541.9 *v.* 744.3 ha (37.4% difference).

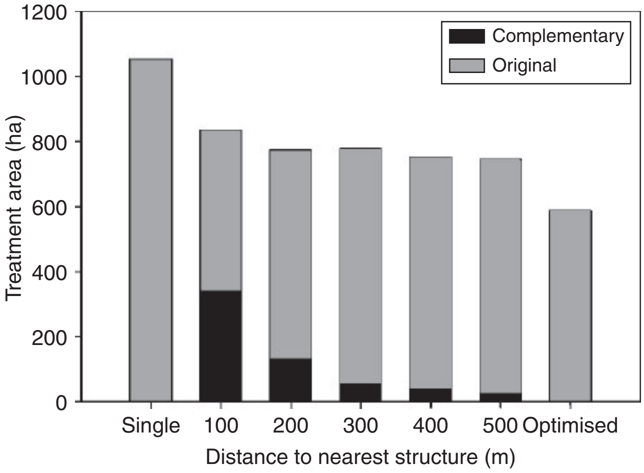


**Fig. 5.** Total treatment area of the alternative fuel treatment delineations. ‘Single’ is non-clustered delineation, 100–500 m are the five clustering distances, and ‘optimised’ is the optimised combination of all previous six delineations. The black areas represent the complementary individual structure treatments required for schemes that did not contain all structures.

When we ranked treatment units according to the number of structures, we found that a relatively small number of units contained a large fraction of the overall treatment area and protected a large number of structures (Fig. 8 top). These areas correspond with the dense development around the lake chain in the centre of the study area, where the largest treatment units were located, and which contained the majority of houses. For example, protecting 51.4% of the structures in the study area required only four treatment units, which covered 182.7 ha (31% of the total treatment area).

When treatment units were ranked according to fire risk (i.e. the sum of fire risks for all structures within a unit), a similar

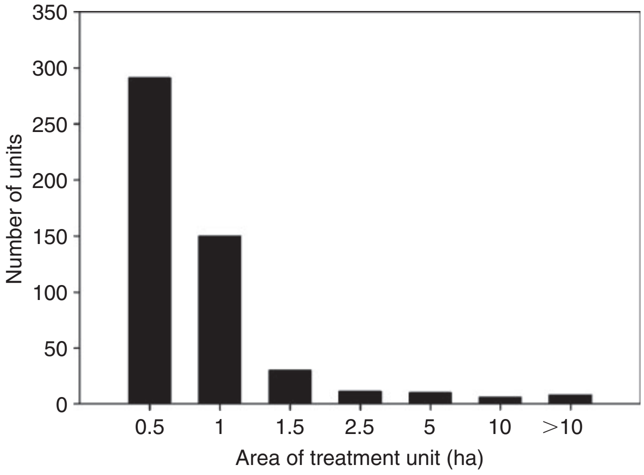


**Fig. 7.** The area distribution of the optimised treatment units.

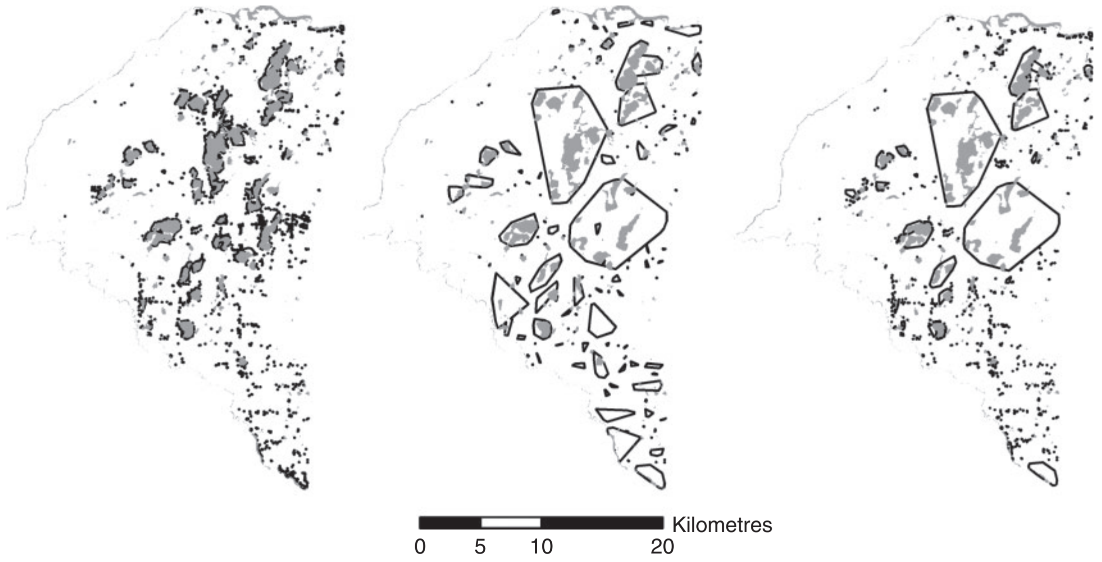


**Fig. 6.** Three treatment allocations (in black) with varying clustering distances: 100 m (left), 500 m (middle), and the optimised allocation (right). Lakes are shown in grey.

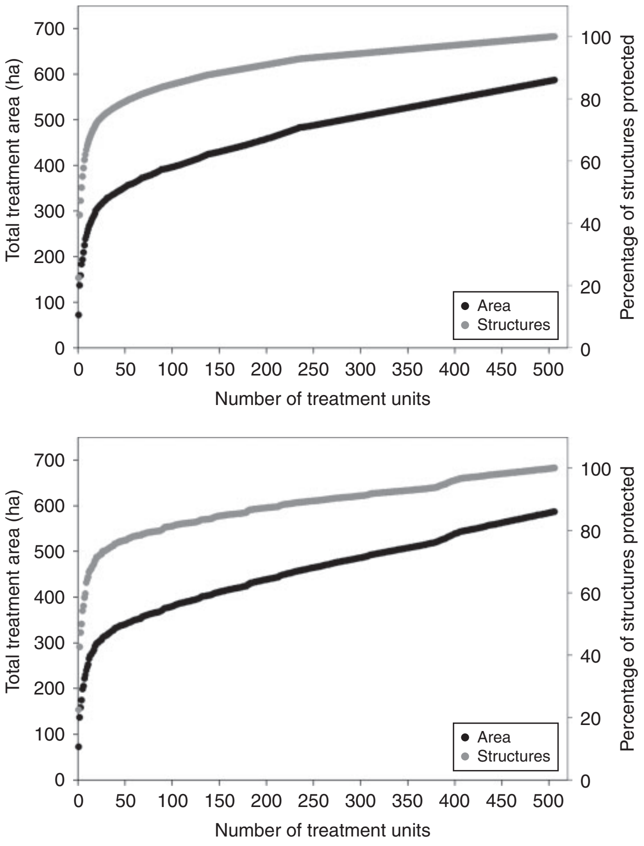


**Fig. 8.** Accumulation curves of total treatment area (left *y* axis) and percentage of structures under fuel treatment protection (right *y* axis) for two ranking schemes (i.e. the data are the same, but the order of data along the *x* axis is different). Top – units ranked according to area; bottom – units ranked according to fire risk to structures.

saturation curve was obtained, but it was less smooth (Fig. 8, bottom). This indicated that there were cases where smaller units had greater fire risk than larger units, and so they were given a higher ranking. The two different ranking schemes produced divergent results starting from the third treatment unit. In the top-ten-ranked units, there were six discrepancies between methods, and many more appeared lower in the rankings as well.

### Delineation accuracy

Though the fuel-break allocation algorithm performed well most of the time, there was a special case in which treatment position was suboptimal. This occurred when convex polygons were formed around clusters of structures that were separated by non-fuel areas (lakes). In some cases, line segments that connected two points that were separated by a lake were not optimally positioned (i.e. not having the shortest path to the lakeshore). This happened because a convex polygon was formed based on points on both sides of the lake simultaneously, making the correction method described earlier inefficient. The effect of this phenomenon was assessed by manual correction of 10 treatment units, followed by a calculation of the change in area. We found that the difference in treatment area was only 1.01% (the automated delineation fuel breaks were larger than they should have been). In addition, this inaccuracy affected only a small number of treatment units. Combining those, we concluded that the overall effect of this inaccuracy was negligible.

## Discussion

Wildfire risk assessment, prevention and mitigation have emerged as focal points of fire management and WUI research in recent years, owing to their potential consequences for human lives and structures. Wildfire prevention and protection have been applied at two scales: parcel- or homeowner-based actions in the HIZ, such as vegetation management and fuel removal from the immediate vicinity of structures and the use of fire-resistant building materials; and organisational scales, in which fuels are managed at larger scales and across ownerships, either near settlements or roads, or deeper in the wildlands. Cohen (2000) showed that the local scale is the most important in protecting a structure from burning, especially in areas where home ignitions are caused by spotting. Homeowners can make significant changes to their structure and their lot that reduce the risk of home ignition, but for a host of reasons ranging from lack of awareness to limited resources to a home being left vacant, parcel-based action is not universal, and each homeowner's failure to manage their property can impact adjacent properties. For this reason, communities have an important role to play in providing WUI-based fuel management at broader scales as well. Our results showed that broad-scale fuel management (i.e. protection of a group of structures rather than each individual structure) can reduce overall treatment area and hence treatment costs. These results are especially relevant in regions where home ignitions are caused by surface fires (that often can be blocked by fuel treatments) rather than from spotting.

Although several analytical approaches for planning fuel treatments in the wildlands have been developed (e.g. Finney 2001; Bevers *et al.* 2004; Kennedy *et al.* 2008), there is a lack of research that attempts to do so in the WUI aside from the HIZ approach. When HIZ is not feasible, the most basic question that needs to be answered before planning fuel treatments in the WUI is what should be protected – single houses or groups of houses? If the latter is optimal, then the question arises what defines a group of houses, and how should a treatment be placed around them?

Here, we introduced a basic approach to fuel-treatment delineation in the WUI. The approach was based on determining the optimal clustering of structures so that the overall treatment area in the landscape was minimal, while treatment locations were still close (if not immediately adjacent) to the structures. Initially, the approach surrounds all structures with treatment units (either as individuals or as clusters). To account for limited resources, we also developed a ranking system, in which treatment units are ranked according to the number of houses or their corresponding fire risk. In this manner, it is possible to choose between units in cases where there are limited resources for treating the entire area.

Being a basic method, our approach ignored issues of ownerships and the location of critical infrastructure, and we simplified structures as being point-based rather than analysing their exact shape and size. However, converting our approach to incorporate ownership (and other) limitations is conceptually straightforward. In addition, we tested only a single type of a simple fuel treatment (30 m-wide fuel breaks), but it is possible to model other fuel-treatment types as well because the delineation algorithm can place treatment units regardless of treatment type. We note though that there is no single fuel treatment that can reduce fire risk to zero, as WUI ignitions can result from spotting fires that can originate from several kilometres away. Ignition by embers has to be reduced by using fire-resistant building materials, or reducing ember production by applying fuel treatments that limit crown fire or reduce fire severity in a much larger area around the structure (Bevers *et al.* 2004), which is often not feasible. However, the 30-m fuel break used here can greatly reduce the ability of a crown fire to ignite a house and may completely halt a surface fire. Alternative treatments, which our algorithms could place just as well, include shaded fuel breaks (removal of all surface vegetation while keeping the trees), thinning (decreasing tree density), or a combination of both. These treatment types have less drastic visual consequences, and as such may be more implementable in WUI areas where homeowner acceptance of fuel treatment options is often important.

The main problem of our proposed method is that the objective function, which minimises overall treatment area, does not necessarily lead to the best wildfire protection. Large, dense clusters of structures are often protected by a single fuel break, because it takes less area to surround them all than to surround each individual structure. This leads to cases where significant amounts of wildland fuel are contained within the treatment unit. Coupled with the tendency of ignitions to occur near structures, this may lead to cases where all structures within a unit are vulnerable to a wildfire that is initiated within the treatment unit, i.e. by embers (though conversely, the outside wildland would be protected from such a WUI-based ignition). To guard against an internal ignition, each house will need to be protected separately. Thus, the purpose of a minimal area-based fuel-treatment allocation as suggested here should be to complement structure-based treatments in the HIZ and offer an extra layer of protection at the community level, rather than to be the sole solution for wildfire protection.

Another issue to consider when applying our algorithm is that fuel treatment costs depend not only on area, but also on vegetation type and structure, terrain properties (slopes), and accessibility of treatment areas. Fuel treatments are cheaper and easier to apply in areas with less vegetation, flat terrain, and better access. Our current algorithm accounted for extreme cases of this phenomenon by incorporating existing firebreaks (i.e. lakes) in the treatment plan, and it would be straightforward to account for roads and other non-vegetated areas as well. However, prioritising treatment locations according to fuel types, terrain and accessibility is more complicated, because the costs of treating each type would have to be accounted for. Moreover, collecting data about current fuel type and structure (which is required for planning the construction of fuel treatments) will cost money. In areas of mixed public and private ownership, this raises the question of who should pay for data collection. Local conditions thus will ultimately determine if placing fuel treatments based on treatment area is meaningful or not.

In ranking the individual treatment units, we used fire-risk information that was generated by fire simulations in a previous study (Bar Massada *et al.* 2009). In that study, we used FARSITE and MTT to simulate fire spread. However, the FARSITE and MTT models simulate fire spread and behaviour for wildland fuels. Wildland fires may be different from WUI fires, because the WUI is different from the wildlands in terms of fuel type and configuration, owing to the existence of non-natural fuel types (i.e. structures), which may have a considerable effect on fire spread. For example, roads may act as fuel breaks, while houses constructed from flammable materials may burn more severely than natural fuels. Roads were accounted for in the simulations by adding them to the fuel maps as non-burnable fuels, but houses were not incorporated into the fuel maps owing to the lack of data. This may have affected the behaviour of the simulations in housing areas, and as such may have biased the estimates of risk, which in turn would have affected the ranking of the fuel treatments. Therefore, in order to incorporate fire risk in the ranking of the fuel treatments generated by our optimisation approach, it is necessary to account for the limitations of fire simulation models in WUI environments.

In addition to fuel-treatment delineation, the clustering method proposed in this study may be applicable to other cases where housing interacts with wildlands. For example, cost-effective fencing may be used to block access of wildlife into built areas. Additionally, clustering and buffering may be used to prevent flow of invasive species from the built areas into the wildland areas.

Allocating fuel treatments in the WUI is a complex problem with many implications, which deserves intensive research in order to find means for reducing wildfire risk to humans and structures. Although actions in the HIZ (fire-resistant building materials and removal of adjacent fuels) will always minimise ignition risk to houses the most, in many regions where crown fires are rare and surface fires predominate, the costs associated with these practices could perhaps be reduced by treating fuels around houses or even communities rather than the houses themselves. Assuming that management agencies should play a role in this task (in addition to the much-needed cooperation of property owners), it is desirable to develop analytical means for fuel-treatment delineation beyond the boundaries of individual properties. The method that we presented in this research may serve as a preliminary step towards achieving this purpose.

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