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Garden design can reduce wildfire risk and drive more sustainable co-existence with wildfire

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Destructive wildfire disasters are escalating globally, challenging existing fire management paradigms. The establishment of defensible space around homes in wildland and rural urban interfaces can help to reduce the risk of house loss and provide a safe area for residents and firefighters to defend the property from wildfire. Although defensible space is a well-established concept in fire management, it has received surprisingly limited scientific discussion. Here we reviewed guidelines on the creation of defensible space from Africa, Europe, North America, South America, and Oceania. We developed a conceptual model of defensible space framed around the key recommended approaches to mitigate fire attack mechanisms, which address fuel types, amount, and spatial distribution. We found that zonation within the defensible space is commonly recommended; reduction (or removal) of all fuels, and particularly dead plant material, is usually suggested in close (< 1.5 m; Fuel-free zone) proximity to a house. Conversely, in an intermediate space (1.5–10 m; Open zone), guidelines focus predominantly on minimizing fuel horizontal and vertical connectivity. Finally, in the outer part of the garden (10–30 m; Tree zone) trees can provide canopy shielding from ember attack and radiant energy, but management of on-ground fuel is still recommended. Evidence from the scientific literature broadly supported these defensible space design elements, although many studies were highly localised. Further empirical and modelling research is required to identify optimal zonation surrounding houses, and to better understand how garden structure, species composition and moisture status affects risk of ignition from embers, radiant heat, and flames.

Anthropogenic environmental changes are altering the global frequency and severity of wildfires. Weed proliferation, land abandonment, and fire suppression have increased fuel loads leading to more intense fires, while anthropogenic climate change has increased the length of fire seasons and the occurrence of extremely dangerous fire weather[1–7], even for vegetation types not historically fire prone[8]. Such fire regime changes pose threats to human communities and ecosystems[2], particularly in the Wildland-Urban and Rural-Urban Interface (WUI and RUI respectively, and WRUI henceforth), where suburban and semi-rural communities interface or are intermixed with natural vegetation[9–15]. Population density is typically low, although with major geographic differences[10]. A compounding factor is that WRUI areas have a high frequency of human-ignited fires[16,17] making these settings a key locus for house loss disasters[18]. For instance, it has been estimated that in Australia the majority of house loss typically occurs within 100 m from natural vegetation[19].

Because the natural and anthropogenic aspects of the WRUI are tightly interwoven, wildfire risk management is extraordinarily complicated, involving biophysical and socio-economic dimensions that impinge on wildfire prevention, preparation, and suppression strategies associated with limiting fire spread and intensity from surrounding wildlands whilst mitigating property fire risk[20–22]. How to best manage wildfire risk of at the WRUI has been debated for decades[23,24], with proposed solutions including urban design[25], early fire detection[26], aerial suppression through rapid attack[27,28], and wildland fuel treatments. Yet, no consensus or demonstrated effective strategy has been achieved. Solving this problem is becoming urgent because of the observed expansion of the WRUI[29–32], which has led to increased occurrence of disastrous fires, surging firefighting costs[9,33], and more costly home insurance causing an epidemic of under-insurance[34].

Current approaches to managing fire risk on the WRUI carry a range of constraints and adverse side-effects. Aggressive fire suppression can create a

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'fire suppression paradox' that encourages urban settlement in hazardous landscape settings[35], and can reinforce negative feedbacks through vegetation change and fuel build-up, leading to more extensive and destructive bushfires[36]. The most prominent wildland fuel treatment is prescribed burning, which involves fires intentionally set under favourable conditions to reduce fuel loads in wildlands. There is, however, mounting evidence that the approach has a modest protective effect for house loss unless it is in close proximity to urban areas[37], but problematically this necessitates careful, costly and oftentimes legally challenging coordination of different landowners[38,39]. Prescribed burning also has many downsides including: being ineffective in extreme fire weather conditions, which are increasing in frequency due to climate change[40]; having a risk of escaping control[41]; causing smoke pollution and substantial health harms[42]; and potential loss of biodiversity[43]. Further, there is no clear social or community preference for a specific type of intervention to reduce wildland fuels, with individual opinions affected by personal values and knowledge of local ecosystems[44–47]. Finally, there is emerging evidence that in some highly flammable environments, such as Australian eucalypt forests, a focus on long-term wildland fuel management might be legally, financially, and ecologically unsustainable[48].

A commonly officially recommended, yet comparatively less-researched option in mitigating fire risk in the WRUI involves modifying urban areas to increase their ability to survive bushfires by focusing on building construction and design, as well as creating low flammability zones surrounding houses, known as 'defensible spaces'[49]. The US Forest Service defines the defensible space as the area surrounding a house where the space has been modified to reduce the threat of wildfires by removing, reducing, and replacing elements of the space that increase fire hazard (USDA Forest Service). Models based on post-fire assessments revealed that garden characteristics, particularly vegetation type and cover near the house[50–52], as well as presence of non-vegetative fuels[53,54], affect the likelihood of house loss. In one case, they were found to be more important than building characteristics in determining house survival[55]. Creating and maintaining effective defensible space means that residents are more likely to be able to stay and defend the property and that it is safer for firefighters to engage with a house fire without fear of entrapment[56]. Homes are also more likely to withstand a fire if defended[57].

The underlying logic and biophysical basis of definitions of defensible space has received surprisingly limited investigation. Reviews on the defensible space are scarce and focus predominantly on house design, construction building regulations[58,59], or framing it as a core component mitigation on the broader WRUI[60]. What is lacking is a synoptic overview of defensible design principles that can lead to a more theoretical understanding of defensible space framed in terms of physical principles that affect wildfire occurrence and behaviour, based on evidence of the importance of key variables that shape these physical processes.

Here we proposed a conceptual model of defensible space based on the main mechanisms of wildfire behaviour and the key wildfire mitigation strategies, the latter obtained from a review of the guidelines for the establishment of defensible space. To identify consistent themes across a wide range of geographic settings, we searched guidelines written in (or translated in) English, French, Italian, or Spanish, using the keywords 'wildfire defensible space', 'bushfire defensible space', 'wildfire home preparation', 'espace défendable incendies de forêt', 'incendi spazio difendibile', 'espacio de autoprotección'. Since many of the guidelines are considered grey literature, we did not limit our search to academic search engines (Web of Science and Google Scholar) but also included a general search engine (Google Search), in which we included as search term country-specific domains of countries with high fire activity and presence of WRUI (Fig. 1). Results were then screened to include only documentation that explicitly addressed defensible space design. We collated information from 68 guidelines from Africa (South Africa), Europe (France, Greece, Italy, Portugal, and Spain), North America (Canada and United States of America), Oceania (Australia and New Zealand), and South America (Argentina and Chile) (Fig. 1). Guideline sources included federal and state government departments or organizations, local councils, universities, and independent organizations (e.g., Australian College of Architects). A full list is available in Table S1 in Supporting Information. Drawing on these guidelines, we discussed the core elements of the defensible space aimed at maximising its effectiveness in relation to wildfire threats. For each component of this framework, we then presented existing evidence from the scientific literature, to identify concordance of guideline design elements with empirical research as well as identifying knowledge gaps. Such a framework is an essential step to effectively quantify defensible space on the WRUI and support the creation of fire-resilient landscapes[61].

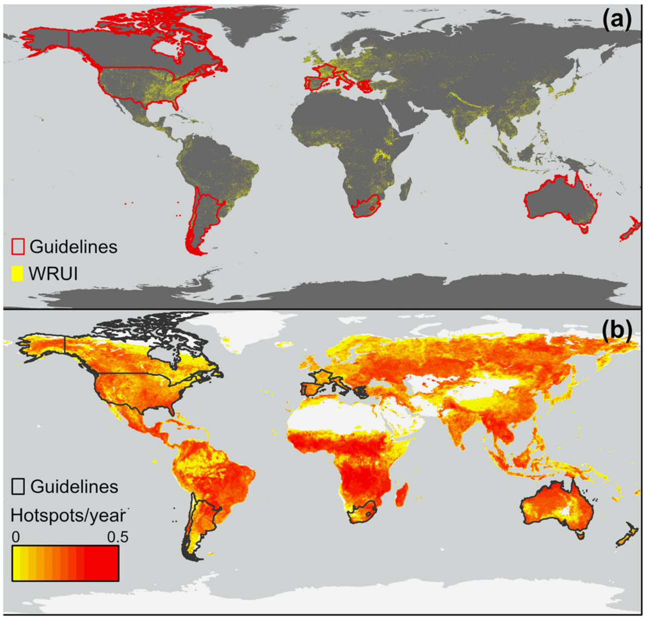

Fig. 1 | Location of the countries for which guidelines on the creation of defensible space could be sourced. Countries are shown in relation to (**a**) the location of the WRUI (data from Chen et al.)[15] and (**b**) fire activity, intended as the number of hotspot per year between 2000 and 2021 (data from Kelly et al.)[4].

Bushfire attack mechanisms

The concept of wildfire defensible space hinges on its capacity to stop radiative and convective energy crossing a critical heat flux threshold and causing a house fire[62]. Energy transfer can occur through three mechanisms: direct flame contact, radiative heat, and firebrand attack (Fig. 2).

Direct flame contact includes both convective and radiant energy and is potentially the most hazardous wildfire house-loss mechanism, as it has the highest heat fluxes, with temperature reaching 1,000°C[63,64]. By providing a source of flames (piloted ignition), it also lowers the temperature required to ignite fuel[65]. It is, however, limited by the ability of flames to reach the house[62]; protective factors thus work by separating wildland and domestic fuels. Post-fire assessments show that proximate flame contact is an important, albeit not necessarily the predominant, cause of house ignition[53,66,67].

Radiant heat, defined as electromagnetic radiation emitted from thermally hot bodies, can cause structure ignition if sufficiently intense[68]. For instance, it can cause window breakage[69], thus exposing the interior of the house to flames and firebrands. Field experiments showed that radiant heat fluxes generated by wildfires can reach up to 300 kW/m^2[70], well above the threshold of 13 kW/m^2, which has been found to be sufficient to cause wooden building ignition[71,72]. As such, the Australian Bushfire Attack Levels that are used for determining the building specifications of homes in bushfire prone areas are based around assessed radiant energy loads (kw m^{-1}). As radiant heat is proportional to the inverse of the square of the distance from the source[68], its threat to the house and people defending it diminishes progressively as the heat

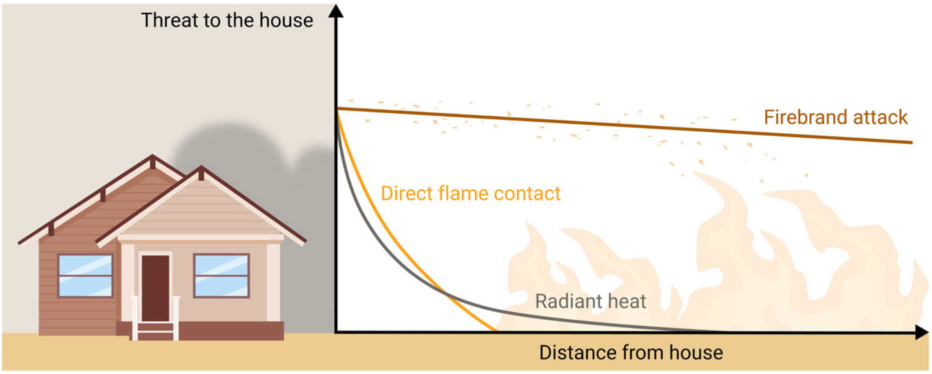

Fig. 2 | Conceptual diagram showing the three wildfire attack mechanisms and the threat they represent depending on the distance from the house. Direct flame contact represents a high risk, but only in proximity to the house. Radiant heat constitutes a high risk near the house, but quickly declines as the heat source is located away from the house. Conversely, the risk caused by firebrand attacks only slightly decline with distance.

source is located away from the house (Fig. 2). However, radiant heat is a common cause of bushfire fatalities[73], as skin burns and blistering can occur within a few seconds of exposure to heat fluxes well below structural ignition thresholds[74].

Firebrands, the third bushfire attack mechanism, are airborne flaming or smouldering fuel particles, lifted by the plume of fire gases and carried horizontally by winds. Firebrands can impact properties i) directly, by setting on fire structures and vegetation within the defensible space, and ii) indirectly, by creating additional fires (spot fires) ahead of the main fire front[75]. They can travel up to more than 30 km from the main fire front[76], although an analysis of 4000 spot fires in Australia found that only 10% of firebrands reached beyond 1 km[77]. As such, they are widely recognised as a common cause of house loss at the WRUI[54,67].

A conceptual model of wildfire defensible space

The sourced guidelines for the creation of defensible space translate this physical concepts into actionable recommendations that can be grouped in three key and closely related fuel characteristics: type, amount, and spatial distribution. Fuel type determines ignitability from embers, shapes energy release and hence convective and radiative energy, as well as fire behaviour including rate of spread. Fuel amount (or fuel load) affects total energy release, while fuel spatial distribution influences the probability of flame contact with a house or spread between vegetation patches, firebrand density, and radiant heat load should the fuel ignite. Based on this framework, we grouped specific guideline recommendations according with the risk factor they address (fuel type, amount, or spatial distribution; Tables 1, 2 and S2 in Supplementary Information) and reviewed the concordance with evidence from the scientific literature.

Fuel amount

The concept of modifying fuel loads surrounding homes is central to all guidelines for the creation of defensible space. When guidelines recommend a specific defensible space extent, they typically focus on a 30–40 m radius from the edge of the building or up to the property line, whichever is shorter, particularly in Africa, North America, and South America (Fig. 3; Table 1). In Europe, particularly in Portugal and France, the recommended distance can be up to 50 m[78,79]. When the minimum distance is shorter than 30 m, guidelines often recommend consideration of slope angle and surrounding vegetation type, leading to larger recommended defensible space if not on flat ground (e.g., France[79], Portugal[78], Italy[80], Canada[81], United States[82], and Australia[83]; full list available in Table S2 in Supplementary Information). This is because fire usually propagates faster uphill due to the increased amount of fuel exposed to radiant heat and direct flame contact[84,85], although in some settings extreme fires can progress downslope (e.g., driven by Foehn winds[86]) or along a valley or lee slope (i.e., vorticity-driven lateral spread[87]). The main strategy to reduce fuel amount involves thinning vegetation, removing dead plant material, keeping lawn grass short, and reducing canopy cover (Table 1). In New South Wales (Australia), guidelines recommend not exceeding 15% of canopy cover across the whole defensible space, with lower values (10%) for shrubs[88] (Table 1, Table S2 in Supplementary Information). More specific guidelines on fuel amount are usually provided for each section of the defensible space (see ‘Fuel spatial distribution’).

Overall, the scientific literature supports the recommended extent and general characteristics of the defensible space, although the evidence is relatively scarce. Post-fire geospatial analyses of house loss have shown a statistically significant effect of the characteristics of gardens surrounding houses up to 30–40 m[57,89]. Similarly, models on radiant heat as a cause of house ignition suggested that the threshold distance ranges between 20 m and 40 m depending on the model used[71,90,91]. Finally, a study on crown fires in lodgepole pine (*Pinus contorta*) forests measured the maximum flame length to be approximately 30 m[92]. Research that considered the effect of canopy cover within the whole defensible space found vegetation cover to be an important predictors of house loss[57,89,93], with every 10% reduction in vegetation cover around houses (if remnant Australian native vegetation, which is typically highly flammable) associated with a reduction in the likelihood of house loss of approximately 5%[51]. This combined evidence supports the notion that the overall extent of the defensible space recommended in guidelines can contribute to mitigate fire risk, although caution must be exercised in generalising the findings of localised studies.

Fuel type

Typically, defensible spaces include gardens. As such, the most common fuels are living and dead phytomass (live plants and leaf litter, fallen branches, dead grasses and forbs). Plant flammability, broadly defined as the capacity of plant material to ignite and sustain a fire, is typically represented by four axes: ignitability (ability of a plant to ignite), combustibility (heath released), sustainability (burn duration), and consumability (biomass combusted)[94]. These parameters vary across plant species due to leaf moisture content, leaf morphological and chemical traits (e.g., chemical composition, particularly oils, leaf type and arrangement), plant architecture, and bark characteristics[95]. There are numerous lists on the likely flammability of plant species that are typically grown in gardens, either based on knowledge of local species or plant traits, and the majority of guidelines recommend selecting low-flammability species across the whole defensible space (Fig. 4a; Table 1). However, those lists are not always validated by empirical studies. Whilst a study of native and non-native plants in New Zealand found a reasonable agreement between expert opinion and laboratory flammability assessments[96], other studies could not validate all plant recommendations, which can also be conflicting across different guidelines[97]. Further, although research on plant flammability has been conducted for decades[95,98], and some of those studies specifically targeted native and exotic plants at the WRUI[99–101], the variety of assessment methods adopted limits cross-study comparisons[102].

Ground cover also affects garden flammability. Similarly to plant flammability, the flammability of the litter that accumulates underneath plants is also influenced by species characteristics[103]. Additionally, the spreading of organic materials (e.g., pine bark, wood chips, straw, cardboard

Table 1 | Summary of the key guidelines provided for the whole defensible space within each of the investigated regions

Category	Recommendation	Africa	Europe	North America	Oceania	South America
	FUEL AMOUNT					
Vegetation	Keep lawn grass short	1,4	5, 63		38, 39, 49, 50, 56	
	- Specify max grass length			28	37, 43, 52, 58, 59	
	Thin trees and shrubs		8, 63	10	39, 41, 52, 58, 60	
	- Specify max canopy cover				35, 39, 43, 59	
Dead plant material	Remove dead plant material	2	8, 63	16, 24	36, 39:41, 43, 44, 49, 50, 52, 55, 56, 59:61	68
	FUEL TYPE					
Plant selection	Choose plants with low-flammability traits	3,4	5, 6, 63, 64	9, 12, 22:24, 27, 29:33	35, 36, 38, 39, 42, 43, 47:50, 52:57, 59, 61, 62	66
	List of plants to add and/or avoid	2, 3	6, 7, 63, 64	9:11, 19, 21, 22, 24, 27:29, 31:33	35, 41, 42, 48, 53	
	Remove flammable vegetation	2				
	Use non-flammable material or low-flammability plants to create barriers and wind breaks		5	16	34:36, 39, 42, 48, 49, 55, 56	
Fences	Use non-flammable fencing material	1	63	12, 15, 16, 25, 33	35, 36, 38, 40, 47, 48, 55, 56, 59, 61	
Mulch	Avoid organic (flammable) mulch	1	5	9, 11, 15, 16, 19, 20, 22:25, 29, 31, 33	35, 36, 38:42, 47, 48, 50:52, 55:57, 59, 61	
Water	Keep garden well watered	1,4		9, 22, 28	35, 47, 49, 56	68
	FUEL SPATIAL DISTRIBUTION					
Fuel connectivity: Horizontal distribution	Limit trees and shrubs to small clusters of a few each	1		19, 20, 24	35, 36, 39, 41, 43, 48:50, 52, 56, 59	
	- Specify min distances between clusters	1, 3, 4	5, 64	19, 26	35, 37, 43, 47, 48, 55, 56, 59, 60	
	- Specify min tree and shrub distance from the house				57, 59	
	Use non-flammable material (e.g., gravel) to separate islands of vegetation (break fuel continuity)	3,4	5	11:13, 16, 22, 23, 28, 29, 31, 33	35, 39, 41, 47, 48, 52, 55, 56, 57, 59	
Fuel connectivity: Vertical distribution	Remove lower tree branches			28	41, 48, 49, 51	
	- Specify pruning distances	4	5	19, 20, 22, 26	35:37, 39, 43, 50, 52, 59, 60	
	Remove shrubs and other vegetation from under trees	4		12, 19, 20	35, 36, 48, 50, 51, 55:57, 59	
	- Specify min vertical distance between shrubs and trees	1		24		

Numbers refer to the guideline ID provided in Table S1 in Supplementary Information.

that is generally known as 'mulch') is typically used in gardening practices to reduce evaporation from soil and increase plant water availability[104], as well as controlling weeds, improving soil health and garden aesthetics[105]. Because of the potential flammability of even the most ignition-resistant organic mulch, guidelines recommend avoiding organic mulch and instead relying on non-flammable material such as pebbles and earthen surfaces across the defensible space (Fig. 4a, Table 1). Indeed, research showed that most common types of organic mulch are highly flammable and contribute to fuel horizontal continuity[106–110]. Even the least flammable types of organic mulch can provide receptive fuel beds under continuous firebrand shower[111].

Fences and gates are important fuel elements that can positively and negatively affect garden flammability. Most guidelines recommend choosing fences made of low-flammability (e.g., hardwood) or preferably non-combustible (e.g., steel) material (Fig. 4a; Table 1), particularly if the fence is close to the house or connected to other flammable objects (e.g., mulch, weed beds, trellis). Post-fire assessments have confirmed that fences made from flammable materials (e.g., wood and plastic) can be ignited by firebrands and sustain and spread fire in the garden[112], especially if poorly maintained[66,93]. Conversely, fences made of non-flammable material can shield the house from radiant heat[113]. Other features of gardens such as outdoor mats, outdoor furniture, woodpiles, gas barbeques materials and garden sheds and gardening supplies (fertiliser, weedkiller) are also recognised as 'fuel'.

Within the defensible space, irrigation can mitigate fire intensity by creating a cool moist microclimate that hinders fire propagation[114] and reduces plant flammability[115]. Some guidelines mention the use sprinklers in the defensible space[58], particularly if they are automatically activated through smoke detectors or heat sensors[116], as they can also provide active defence against bushfires, effectively protecting structures as well as vegetation[117]. However, installation costs and ongoing maintenance[117], as well as their reliance on large amounts of water to be effective[118], can lead to low adoption rates[119]. As such, they are best suited for retrofitting existing spaces, while newly designed areas should instead rely on passive defence strategies such as garden characteristics[120].

Fuel spatial distribution

The defensible space is often divided into zones with increasing distance away from the home, each associated with specific amounts, arrangements, and type of living and non-living fuels. The majority of guidelines including zones, and particularly in North America, delineate them as: (a) an

Table 2 | Summary of the key guidelines for the Fuel-free zone

Category	Recommendation	Africa	Europe	North America	Oceania	South America
	FUEL AMOUNT					
Vegetation	Remove plants from near the house or replace with succulents	1		14, 20:22	35	66, 67
	Avoid grasses and lawns			23		
	Limit vegetation to small shrubs		64	29		
	Avoid trees or shrubs	1:3	5	11:14, 18, 19, 22, 23, 25, 28:30, 33	39, 40, 42, 43, 46, 47, 50, 55, 60, 61	68
Flammable material	Remove flammable objects/material (including dead leaves)	1,3	5,6, 63:65	10:13, 15, 17:24, 28:31, 33	36, 38:40, 44:51, 55:58, 61, 62	66:68
	Create a 1-2 m-wide surface made of non-flammable material		6, 63		55	
	FUEL TYPE					
Vegetation	Maintain a well-kept lawn			11, 29, 30	39	
	FUEL SPATIAL DISTRIBUTION					
Zone extent (distance from the house)	1.5 m		65	11, 13:18, 20:22, 25, 28:33		
	2 m		6			66, 67
	3 m	3				
	Not specified	2,4	5	10	34:40, 42, 43, 55, 60:62	
Horizontal distribution	Surround islands of plants with rock or brick retaining walls			22		
	Remove or prune plants near windows		6	14, 17, 21	34, 35, 56	
Vertical distribution	Specify max plant height	2			43, 55	
	Do not store flammable objects underneath decks or under the house	1	6, 63	13, 14, 17, 18, 21, 25, 31, 33	51, 61	

Numbers refer to the guideline ID provided in Table S1 in Supplementary Information.

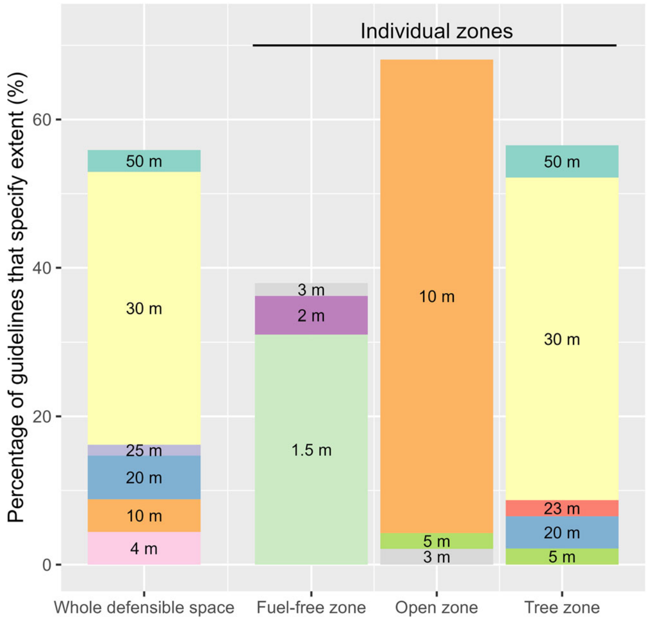

Fig. 3 | Proportion of guidelines recommending a specific minimum extent of the defensible space. For those guidelines that address individual zones, the proportion of guidelines suggesting each specific distance is shown.

immediate zone within 1.5 m from the house (henceforth Fuel-free zone), (b) an intermediate zone between 1.5 and 10 m from the house (henceforth Open zone), and (c) an extended zone, between 10 and 30 m (henceforth Tree zone) (Fig. 3; Tables 2–4). Australian guidelines combine the Fuel-free and Open zones into an 'Inner zone'. Ideally, the Fuel-free zone should have no dead plant material or any combustible objects/material, particularly under the house or deck, and vegetation should be avoided or limited to short lawn grass and possibly succulents, to reduce risk of direct flame and ember ignitions.(Fig. 4b; Table 2).

By contrast, in the Open zone the key focus is to manage vegetation and non-vegetated fuels to interrupt horizontal and vertical connectivity, thus minimizing fire spread towards the house or at least limiting it to low intensity surface fires (Fig. 4c; Table 3). To ensure horizontal fuel disconnection, guidelines recommend managing lawn grass length, distance of shrub patches between each other, and use of paths made of non-flammable material (e.g., gravel, earth, paving stones) to break fuel continuity. Vertical connectivity is avoided by pruning the lowest tree branches to separate them from the fuels underneath and carefully considering all possible connections between vegetated and non-vegetated fuels (e.g., mulch to fences, litter and bark to shrubs). When specific information on minimum horizontal and vertical separation between fuels is provided, values tend to vary between guidelines. For instance, the minimum horizontal distance between crowns can range between 2 m and 10 m and the recommended tree distance from the house between 3 m and 10 m, while the minimum vertical distance between lower adult tree branches and underneath fuels is usually 2 m to 3 m (Table 3; Table S2 in Supporting Information). Despite the focus on spatial arrangement, fuel load should also be limited in the Open zone, especially dead plant material and flammable objects, and vegetation cover should be minimized (Table 3).

Finally, in the Tree zone the primary aim of fuel management is to retain trees to absorb radiant energy and capture embers, whilst reducing surface fuel loads to limit the intensity and spread of fires, and risk of crown fires (Fig. 4d). Possibly because of its distance from the house and the lower threat that fuels in the Tree Zone represent, guidelines tend to be generic or, when specific, they are subject to substantial variation. For instance, recommended maximum canopy cover vary between 15%[121] and 50%[78] and several guidelines in North America, Europe, and Oceania still recommend

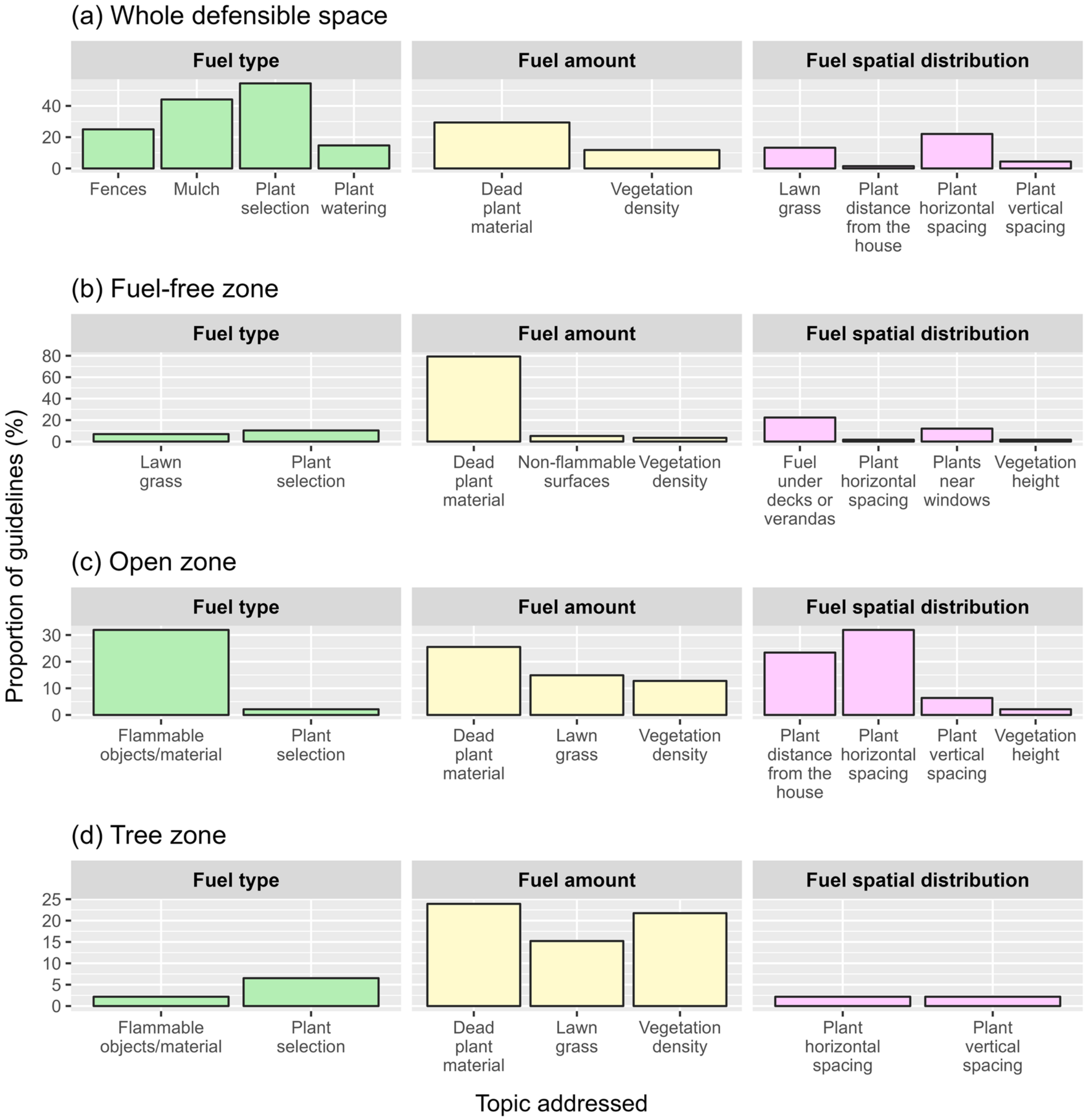

Fig. 4 | Topics addressed by guidelines to describe the ideal characteristics of the defensible space. Topics are summarised (**a**) across the whole defensible space, and within the (**b**) Fuel-free zone, (**c**) Open zone, and (**d**) Trees zone. For each zone (and for the whole defensible space), the proportion of guidelines mentioning each specific topic is shown.

specific minimum horizontal and vertical distances between fuels (Table 4; Fig. 4d; Table S2 in Supporting Information).

Albeit scarce, evidence from the scientific literature does associate vegetation structure in gardens with risk of house loss. For instance, trees and shrubs organized in distinct patches have been linked with lower house-loss risk, especially if positioned in a downwind direction from which wildfires arrive[122]. Similarly, models on the effect of planting arrangement on fire behaviour in urban landscapes concluded that horizontal and vertical fuel separation translates to lower flame heights and slower rate of spread[123].

No study explicitly evaluated the effectiveness of the recommended zone sizes and their respective characteristics. Some indirect support can, however, be found in the scientific literature. Post-fire house loss studies have found that the presence of vegetation in contact with the house increased the chances of house destruction[50,89] Research conducted across a range of vegetation types (grassland, conifer forest, and brush) in the United States showed typical flame length of surface or brush fires to be 1–2 m[92]. These studies indirectly support the establishment of a Fuel-free zone to make the immediate perimeter (< 1.5 m) of houses as fuel free as possible. In respect to the Open zone, an assessment of house loss in California showed that, in regions where the size of defensible space explained at least 1% of the variation in house survival, the average defensible space of the structures that survived the fire was 9.7 m[124]. Further, experimental crown fires have identified the critical structure-to-flame distance that would result in wall ignition as 10 m[71,90], particularly if the fire front length is lower than 100 m[91]. Similarly, flame length in dry eucalypt forests in south-west Western Australia was estimated to be 1–14 m[125].This suggests that the size of the Open zone (1.5–10 m from the house) is possibly adequate to address the risk of direct flame contact (Fig. 5). There is limited scientific literature about the Tree zone. Although not focused on gardens, research on the influence of surface and near-surface fuels showed that their quantity, composition, and arrangement affect fire behaviour[126,127], supporting guidelines recommending management of surface and near-surface fuels in the Tree zone. Vegetation in the Tree zone can effectively shield the house from firebrand attack if made of low-flammability species[55,122], suggesting that tree retention can help to reduce risks associated with firebrand attack.

Table 3 | Summary of the key guidelines for the Open zone

Category	Recommendation	Africa	Europe	North America	Oceania	South America
	FUEL AMOUNT					
Vegetation	Minimize vegetation cover	4	5	14, 28, 30, 31	34	
	Max canopy cover 15%				55	
	Keep grass green and mowed	3	5, 64	11	42, 52, 62	
	Provide info on max grass length			13, 18, 22, 29	34, 55	66
Dead plant material	Remove litter, dead wood, and debris		5, 64	14, 15, 17, 18, 21, 22, 25, 33	52, 55	
	FUEL TYPE					
Vegetation	Mix tall and short shrubs to reduce heat	2				
	Avoid evergreen plants			10, 11		
	Avoid trees and shrubs		65	28		
Flammable material	Do not store flammable material in this zone	4	5, 63:65	10, 14, 21, 22, 23, 25, 28, 30	55	67
	FUEL SPATIAL DISTRIBUTION					
Zone extent (distance from the house)	< 10 m		63	11		
	10 m	3, 4	5, 64, 65	12:18, 20:22, 25, 28:33	34, 42, 52, 59, 60, 62	66, 67
	Not specified	1,2		10	35:40, 43, 47, 55	68
Fuel horizontal connectivity	Trees and shrubs in small clumps	3	64, 65	13:15, 18, 22, 25, 28, 29, 31, 33	52	67
	Provide info on min tree distance from the house		5, 64	15:18, 21, 23, 26, 28, 29, 33		66, 67
	Provide info on min distance between tree crowns		5	5, 10:13, 15, 16, 18, 20, 31, 29, 31, 33		
Fuelvertical connectivity	Remove plants and flammable material from under trees		5	11, 13, 14, 18, 23	52	
	Maintain separation between trees and shrubs underneath		64	18, 25, 33		
	Specify min distance between ground (or shrubs) and lower tree branches		5	10, 11, 13, 14, 18, 21, 29, 31, 33	52	66, 67
	Max vegetation height 1 m		63			

Numbers refer to the guideline ID provided in Table S1 in Supplementary Information.

Discussion

Understanding defensible space is a critical frontier in wildfire adaptation as it provides homeowners a relatively low-cost option to increase the likely survival of homes and lives, compared to the difficulty and expense of retrofitting structures to withstand wildfires[128].

The concept of defensible space is widely promoted by fire managers and is based on logical physical principles to reduce the threat of house loss by minimizing ember ignitions, radiative heat, and flame contact (Fig. 5). Yet, there is surprisingly limited empirical evaluation of defensible space in general and none on the effectiveness of its specific zones, with nearly all studies based on post-fire assessments using geospatial or ground survey techniques[50,54,57,66]. This reliance on inferential studies reflects the obvious practical difficulties of understanding field experiments involving uncontrollable wildfires. Modelling the effect of different garden designs on house loss is a profitable, and little explored, research avenue. To be realistic, however, modelling exercised would require much more field data on how basic parameters such as ember density and radiant heat fields are modified by vegetation and garden design[129].

When clear information from the scientific literature is missing, or consists in few, highly localised studies, guidelines tend to provide more generic recommendations. For instance, the lack of data on the interplay between canopy cover, plant arrangement, and selected species[123] results in most guidelines simply mentioning the importance of spacing between clusters of plants in the Open zone; when more specific recommendations were given, there was inconsistency across guidelines. While this could reflect biogeographic and environmental differences, the difficulty in reconstructing how specific thresholds are determined suggests that guidelines could benefit from more information from rigorous empirical studies. Recent quantitative assessments of plant flammability are a clear example of how the existing flammability lists can be tested and improved upon[96]. Similarly, the increasing availability of high-resolution remote sensing data, such as satellite imagery and LiDAR data, provides the important opportunity to undertake assessments of defensible space on wide geographic scales[130,131]. This will allow to include the characteristics of each zone in post-fire house-loss studies, and thus test the influence of zone extent and characteristics on house survival. In the meanwhile, we argue that implementing a zonation-based approach, which broadly aligns with wildfire physical characteristics, can support the creation of effective defensible space while minimizing maintenance costs and garden constraints, since the stricter guidelines (e.g., minimizing all fuels in the Fuel-Free Zone or ensuring spatial separation in the Open zone) are limited to the portion of the garden closer to the house.

Well-designed defensible space can provide high amenity and promote biodiversity in urban environments on the WRUI. Gardens have been shown to benefit plant and animal biodiversity by improving habitat connectivity and providing habitat for some endangered species[132–136], although their typically high plant species richness is usually driven by exotic species, rather than native[137–140]. Encouraging the use of the local native flora in gardens might have biodiversity benefits but could increase fire risk depending on the flammability of the chosen plant species. For instance,

Table 4 | Summary of the key guidelines for the Tree zone

Category	Recommendation	Africa	Europe	North America	Oceania	South America
	FUEL AMOUNT					
Vegetation	Thin and prune trees	3	5	14, 21, 23, 25, 30, 33	34, 62	
	Specify max canopy cover		6, 63		34, 55	
	Specify max lawn grass length			14, 15, 17,21, 25	34, 42, 55	
	No need to mow grass			18		
Dead plant material	Remove dead plant material	4	64	11, 13, 14, 21, 25, 28, 29, 31, 33		
	- Specify max litter depth			17		
	FUEL TYPE					
Vegetation	Choose non-flammable plants	2	5	22	62	
	Remove small conifers between adult trees			13, 29		
Flammable material	Specify min distance from the house for firewood and propane gas tanks			19, 20, 24		
	FUEL SPATIAL DISTRIBUTION					
Zone extent (distance from the house)	< 30 m		63	14	52, 60	
	30 m	3	64, 65	11:13, 15:17, 20:23, 25, 29, 30, 33	62	66, 67
	50 m		5, 6			
	Not specified	2		28, 31, 32	34:40, 42, 43, 47, 55, 59	
Fuel horizontal connectivity	Specify min distance between trees and/or shrubs		6, 63	12, 13, 15:18, 21, 22, 25, 29, 30, 33	34, 55	
	Specify min tree distance from the house		6	‘		
Fuel vertical connectivity	Remove shrubs from underneath trees		6, 63, 64	14, 18	34, 62	66
	Maintain separation between trees and shrubs underneath			25, 30		
	Specify min distance between ground (or shrubs) and lower tree branches		6, 63, 64	14, 15, 21, 23, 31	34, 42, 55	67

Numbers refer to the guideline ID provided in Table S1 in Supplementary Information.

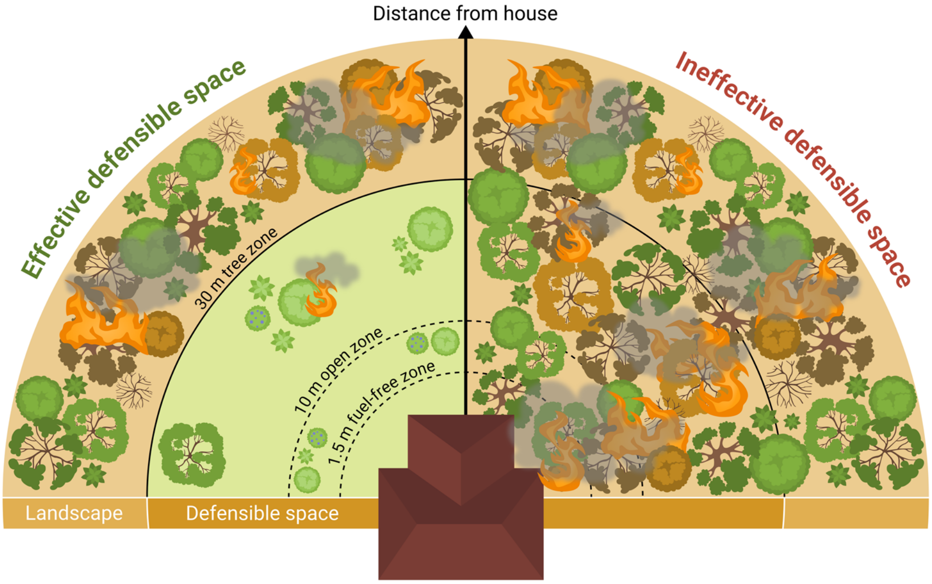

Fig. 5 | Diagram showing examples of defensible space. The left side shows an effective defensible space, with overall low canopy cover, nicely green plants and grass, no vegetation in proximity of the building, and trees and shrubs organised in distinct patches which are not interconnected. With this design a fire approaching from the surrounding landscape would not encroach within the defensible space and, if individual shrubs/trees were to be lit by firebrands, fire would not easily propagate. The right side shows the opposite, where high canopy cover and connectivity facilitate fire spread from the landscape all the way to the house.

exotic species were found to be of higher flammability than native plants in Patagonian gardens at the WRUI[99]. Conversely, in Australia exotic plants in gardens at the WRUI are generally less flammable than native species, although some low-flammability native species were also identified[100]. This suggests that future laboratory assessments might be able to pinpoint native low-flammability options even from typically fire-prone environments. Species selection must also account for current and future local environmental characteristics, particularly in respect to drought tolerance[141]. Garden layout can also contribute to promote local biodiversity without necessarily increasing fire risk. For example, this can be obtained by avoiding needless clearing of trees and ground cover in zones where guidelines are less strict (such as in the Tree zone) or spatially organising plants to minimize fire spread (Open zone). Well-designed, biodiverse defensible spaces have amenity and practical benefits beyond biodiversity conservation and fire safety, such as promoting urban-heat mitigation[123] and improving residents' physical and mental wellbeing[142,143]. Whilst gardens are traditionally based on utilitarian or aesthetic principles[140], wildlife-friendly gardens are increasingly valued[143,144]. Yet, the limited knowledge base about wildlife-friendly gardens[140] limits the ability to design biodiverse and fire-wise gardens.

It is important to acknowledge that defensible space is but one component in mitigating the risk of house loss. In addition to wildland fuel management, particularly in close proximity of property boundaries, and creation of defensible space, the other major factor is house design[124]. These last two components are fundamentally interconnected because a well-designed home may be lost to wildfire if fuel management in the defensible space is insufficient, and a poorly designed house may be still vulnerable to destruction from ember attack even if provided appropriate defensible space. An additional consideration is that the concept of defensible space also includes provision of a safe space for residents to stay with their properties and extinguish spot fires caused by firebrands. The dual objective of protecting property from fires and providing a refuge for residents are typically conflated, despite having different requirements, for example in radiative heat load[74]. The risk of loss of life has led to call for the installation of private fire shelters as a safe place of last resort[145]. Such private fire shelters increase the opportunity for residents to stay and defend properly designed and maintained homes and gardens, although at possibly prohibitive costs.

Finally, a critical field of inquiry concerns the social acceptability of defensible space, and the willingness of residents to pay for the establishment and maintenance of low flammability gardens. This is a crucial step, since the compliance to local guidelines remains a predominantly voluntary process, although an increasing number of countries/states have implemented legal requirements for the creation of defensible space[146–150] and calls have been made to enforce legal obligations in fire-prone areas across Europe[151]. While there can be a positive correlation between wildfire information and mitigation measures[152], residents' awareness of fire risk does not always translate into adaptive action[153]. Understanding the main sociodemographic and economic barriers that limit the adoption of defensible space guidelines and presenting solutions that account for people's preference and focus on community engagement is pivotal to support more fire-adapted communities[154]. Further interdisciplinary research into defensible space is thus an essential step in the broader adaptation pathway for humans to coexist with wildfires on the WRUI.

Data availability

No datasets were generated or analysed during the current study.

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Author contributions

S.O., O.F.P. and D.M.J.S.B. contributed to study conception and design. S.O. searched and summarised the guidelines. S.O. and D.M.J.S.B. led the writing. O.F.P. reviewed and edited the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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