Biomimicry can help humans to coexist sustainably with fire

Globally, flora, fauna and many indigenous cultures have evolved to coexist sustainably with fire. We argue that the key to sustainable contemporary human coexistence with wildfires is a form of biomimicry that draws on the evolutionary adaptations of organisms that survive (and flourish) in the fire regimes in which they reside.

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Recent syntheses have called on humans to coexist with or adapt to future wildfires[1,2]. However, they stop short of making specific suggestions of how to achieve such coexistence. We suggest that for humans to live sustainably with fire, collaborations between urban planners, architects, engineers and ecologists should adopt the principles of biomimicry and follow the lead of organisms and indigenous peoples that have evolved to thrive in flammable environments. Biomimicry involves the development of materials, processes and structures inspired from biological organisms and mechanisms; for example, the development of the material Velcro by George de Mestral after observing how burrs stick to animal fur[3,4]. We present a novel organizing framework that categorizes evolutionary approaches to coexisting with fire and bridges them into the contemporary human system. This organizing framework comprises four primary strategies to coexist with fire (Fig. 1)[5–8].

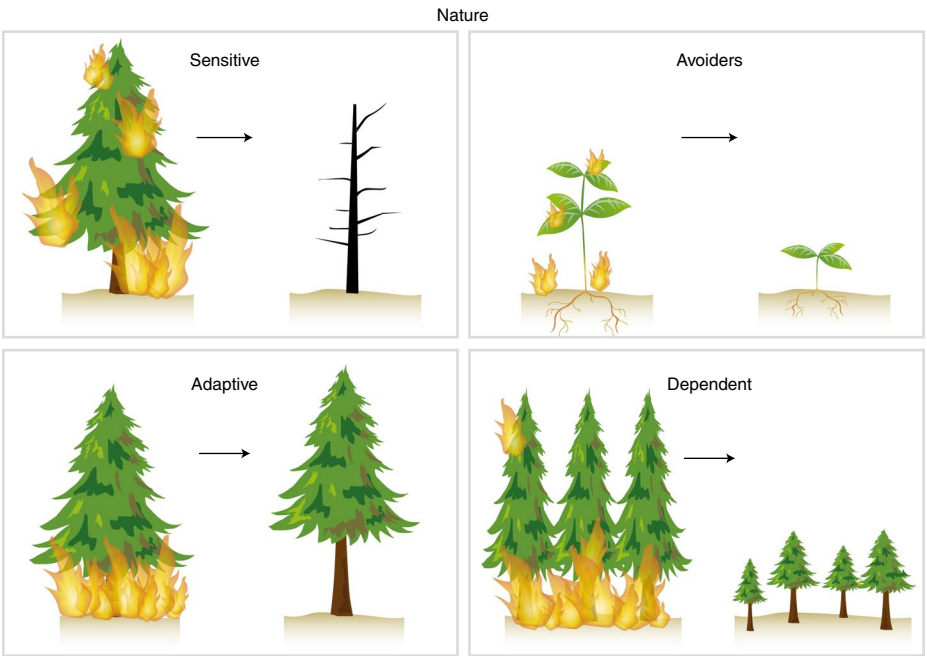

Fig. 1 | Floristic representation of the Sensitive, Avoiders, Adaptive, Dependent (SAAD) model. Fire-sensitive species have no evolutionary adaptations and are killed by fire; they fill niches in places with minimal fire or very long fire-return intervals. Fire-avoiding fauna species generally focus on escaping by fleeing or hiding in safe places, whereas fire-avoiding flora species invest heavily in protecting themselves against immolation by translocating critical resources (for example, carbon, nitrogen) to their roots to create reserves for post-fire resprouting, seeding, regeneration and recovery[5–7]. Fire-adaptive flora developed protective morphological features such as 'armour' (for example, thick insulative bark or sheaths around reproductive organs) and self-pruning of lower branches to reduce fire jumping to the canopy. Fire-dependent flora have evolved to require fire to reproduce (for example, serotinous cones, cued flowering, seed germination by heat or smoke)[6,7], with the added benefit of killing their competition in the process[8].

Fire strategies

Although individual humans can flee fire, human communities are much like flora, in that they can't simply avoid fire. Whereas flora have evolved and adopted a range of adaptive and mitigation strategies and traits to survive fire in situ, contemporary humans have generally forgotten the evolutionary lessons of their ancestors and failed to adopt modern equivalencies to ancestral fire coexistence strategies. Currently most human settlements follow the fire-sensitive strategy of our model. When a wildfire occurs in the peri-urban environment (for example, the wildland–urban interface), the resulting disasters include fatalities, destroyed homes and infrastructure, and substantial economic losses. Fire-avoidance has both intentionally and unintentionally been adopted globally. Wildfires don't consume modern urban centres made of non-flammable materials (for example, steel, concrete, glass). This is a direct product of learning from history; great fires in cities (the 1666 Great Fire of London, the 1835 Great Fire of New York, the 1906 San Francisco fire, and so on) led to enormous efforts to control fire using sophisticated technologies and cultural prohibitions. For example, as Europeans colonized Australia and the Americas, one of the many methods for extirpating both wildfires and indigenous peoples was to characterize fire use as uncivilized and those who practiced it culturally as savages. This ultimately led to a total bushfire ban in Australia under extreme fire behaviour conditions and the full fire suppression policies of the United States, as exemplified by the Smokey Bear campaign[9,10].

Fire-adaptation is central to the concept of defensible space, which promotes 'morphological changes' to properties such as non-flammable exteriors (for example,

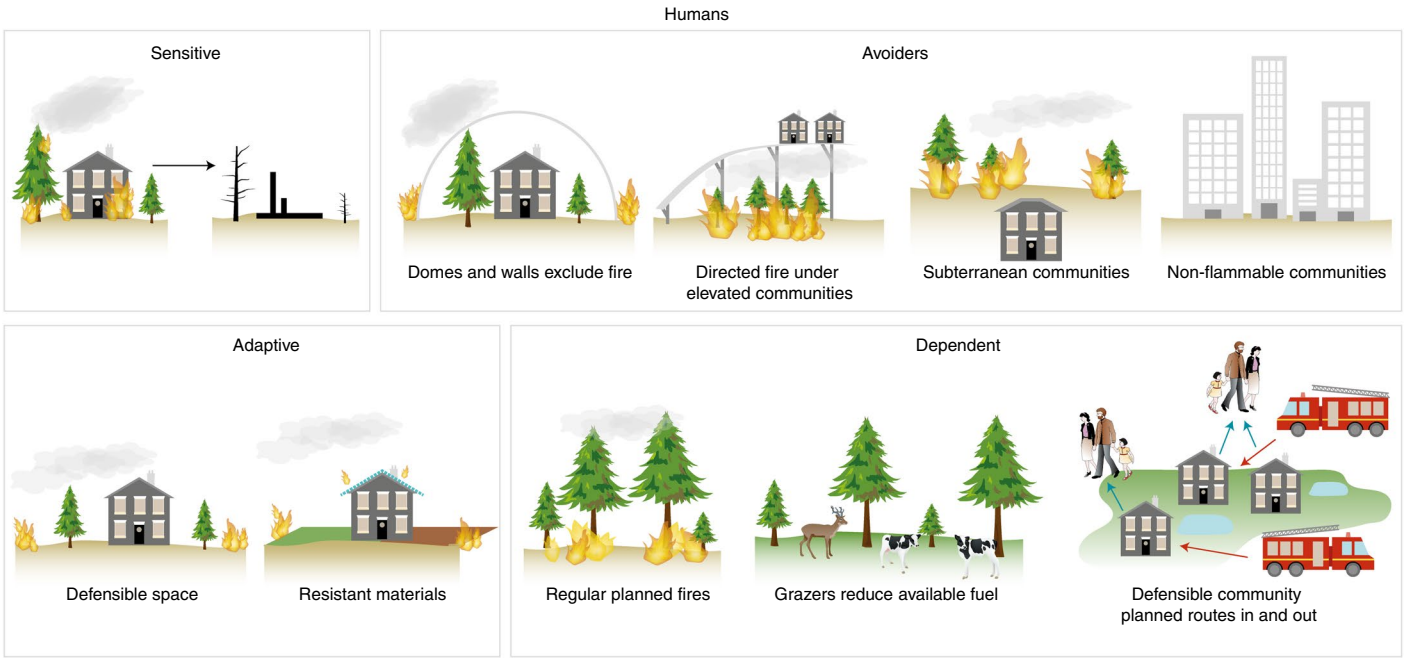

Fig. 2 | Contemporary human system representation of the SAAD model. Through adopting biomimicry, contemporary humans could move past the sensitive paradigm to better avoid, adapt to, or depend on fires. Following flora and fauna, humans should adopt approaches adjusted to the fire regimes in which their communities reside.

roofs, siding, decking) and reducing vegetative fuels within a given radius of a structure. However, in nature this concept works only at the landscape level or above. For example, individual fire-adapted *Pinus ponderosa* trees mixed in with fire-sensitive tree species (for example, *Abies* spp.) are more likely to die than a landscape comprising solely *P. ponderosa* trees. Similarly, an entire community built with defensible space is more likely to survive fire than a single home amidst a community of fire-sensitive structures. There are many examples in peri-urban areas where a single house catching fire has led to house-to-house ignitions, even when other houses had defensible space (for example, the 2016 Fort McMurray fire in Alberta, Canada, or the 2018 Carr fire in California, United States)[11].

Fire-dependence is a strategy with a deep human past[9,10]. Indigenous humans learned to exploit fire to manipulate the movement and concentration of game and support the growth of culturally important plants and foods; in Australia, this aboriginal practice has been termed fire-stick farming[9]. Many settlers depended on fire as a tool of land-use conversion and agricultural expansion[9,10]; this strategy is still in use today in global tropical and sub-tropical ecosystems to clear land. Contemporary fire science unwittingly advocates fire dependence through recommending the practice of extensive prescribed/planned fires. If adopted, a one-time application is not sufficient as a fire-mitigation strategy, but rather fire must be continually reapplied, which leads to fire-dependence. In many parts of the southeastern United States, for example, prescribed fires are conducted near annually to consume the rapidly regenerating vegetation, which has led to fire-dependence in long-leaf pine forests and legal protections around the 'right' to burn[12].

Out of the frying pan

While some progress has been made in identifying and adopting discrete strategies for coexisting with fire, observations and predictions point to increased human sensitivity to wildfire disasters globally[13]. This suggests there is an urgent need to substantially expand upon biomimicry strategies within our model and move humans out of the fire-sensitive paradigm and into one of the other three strategies/paradigms.

First and foremost, fire-avoider human strategies need to include development of official evacuation plans, including pre-determined escape routes and safe shelters, and nationally standardized wildfire early warning systems[14] that are common to other natural disasters (for example, tropical cyclone and tornado warnings, tsunami alerts). At the local government level, urban planners should learn from large fauna that have adapted to evade fire (for example, American black bear, *Ursus americanus*; pronghorn, *Antilocapra americana*)[15] and enable transportation networks in peri-urban areas that readily facilitate ingress of firefighters and egress of residents during wildfire events. This pre-planning is particularly critical in areas where steep terrain has historically featured narrow winding roads, such as in the towns and cities carved into the rocky Mediterranean coastlines of Greece and Italy, where the resultant impaired wildfire response has led to tragedies[16]. Surface and subterranean fauna fire-avoider strategies such as using the insulative properties of soil to hide in burrows and rocky outcrops[15,17] could be readily translated to the human system by optimizing topography and geomorphology to create subterranean homes. Such efforts would be particularly effective in arid and semi-arid landscapes where light and flashy fuels such as grasses and shrubs drive rapid rates of fire spread with low smoke production, so residents would not be 'trapped' underground for long periods while compromised by poor air quality. Earthen and clay homes were features of many indigenous peoples in arid landscapes due to insulation against the climatic extremes found there; such construction effectively addresses multiple hazards. Similarly, burying critical infrastructure such as backup generators and power lines would have the added benefit of reducing a substantial source of wildfire ignitions.

In the United States, the city of San Diego, California, has increased the burial of electrical lines following fatal wildfires sparked by aerial lines in high winds to reduce future wildfire ignitions; other regions where high winds spark electrical fires in flashy fuels would similarly benefit from this strategy.

On the landscape scale, biotic fire-avoider strategies have manifested through the occurrence of refugia, which are often protected from fire by topographic barriers (for example, cliffs, rivers, water bodies)[18]. In the human system, urban centres are already fire refugia because they are dominated by non-flammable materials. Beyond urban centres, this could translate into novel engineering solutions, such as elevating structures above flammable tracts of land where fire is directed to burn (that is, in the same manner that a storm drain directs flood water away from communities), where engineers could learn from topographic and atmospheric processes to encourage inversions to keep smoke away from the elevated platforms. Equally, planners can also create non-flammable barriers between structures and wildlands, and design landscapes that incorporate parks, water features, golf courses and gardens as community fire breaks. Such landscape design principles were incorporated by our recent human ancestors, who created green pastures and orchards around towns for domestic livestock and food production. Modernization has replaced pastures and orchards with suburbs and reforestation, but firebreaks have been developed in many areas of Australia and the United States as golf courses, parks, or open spaces. For example, the Leura golf course in the Blue Mountains of New South Wales functions as a community bushfire safety zone, while the city of Boulder, Colorado, in the United States maintains a buffer of open green space along the Rocky Mountain front that doubles as a fire break.

Some vulnerable homes already emulate the fire-adaptive flora trait of protective bark through use of non-flammable building materials. However, materials scientists could draw inspiration from fire-adaptive flora that use heat shock to trigger germination, such as observed in some *Fabaceae* species[6]. Specifically, the development of coatings that harden or deploy retardant when exposed to heat could help reduce structural ignitions, especially if applied to locations where embers typically accumulate. Learning from flora adaptations to other environmental stressors[19], timber species could be genetically engineered to be more resistant to fires, and structures could adopt comparable traits such as rainwater tanks in roofs[20] or buried underground, with protected pumps and generators that could feed exterior sprinkler systems or line exterior walls. This may help overcome current challenges associated with the duration for which exterior sprinkler systems must run to be effective in a wildfire. Across communities, humans could learn from the spacing of fire-adaptive flora in arid landscapes by creating safe separation distances between homes through elimination of human-made fuels around structures (for example, flammable yard furniture, fences) and adopting community-wide fuel reduction practices.

As a species, humans were fire-dependent for millennia[21]. Our recently developed fear of fire has stemmed largely from losing control of it, brought about by notorious large, deadly fires that have occurred globally (for example, the 1851 Black Thursday fires in Australia, the Great Fire of 1910 in the United States, the 1916 Matheson Fire in Canada, the 1987 Black Dragon Fire in China, the 2010 Russian wildfires, the 2017 fires in Chile, Portugal and the United States, and the 2018 Greece fires). To promote co-existence, humans must regain that feeling of control not through suppression or fleeing from flammable landscapes, but rather through widespread use of prescribed/planned fires as well as rural and urban planning. To achieve this, humans need to learn to balance the trade-offs of smoke impacts with wildfire risk and attune an aesthetic that doesn't idealize living in the woods[22]. Humans in the past, as well as indigenous groups in tropical and sub-tropical ecosystems today, regularly used fire to support agricultural systems and manage ecosystem goods and services[23].

Investment in sustainable coexistence

Biomimicry through our model can help humans avoid unsustainable solutions. Fire-sensitive flora die when exposed to fire and regenerate from seed banks and dispersal of seeds from unburned areas. The analogue in many human communities is the common practice of using insurance and external subsidies (for example, disaster relief) to continually rebuild communities back to the pre-fire state. This arguably treats the symptoms without addressing the underlying fire-sensitive causes. The concealed challenge is one of perceived risk of occurrence to resulting costs and losses[24]. With tsunamis and earthquakes, the probability of occurrence is low, but when they occur, the costs and losses are enormous. The result is that humans build to earthquake codes and have pre-determined tsunami evacuation routes. Wildfires need to be viewed in the same manner, as arguably, it is not sustainable to perpetuate the fire-sensitive paradigm given human sensitivity to fires is predicted to increase[13]. A better approach is for human communities to proactively invest in fire-avoidance, fire-adaptive and fire-dependence strategies (Fig. 2). As seen in fire-adaptive flora, over the long term, this is a more economically efficient strategy than a cycle of destruction and complete replacement inherent in the fire-sensitive strategy.

Globally, flora, fauna and many indigenous cultures have evolved to coexist sustainably with fires within their fire regimes[5,15,21,25]. We argue that to coexist sustainably with fire, contemporary humans must also adapt their communities to current and projected fire regimes. Learning from how nature has led to innovative solutions to improve human resilience to other natural disasters[26,27], only by adopting similar strategies can we truly coexist with fire. ❐

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Competing interests

The authors declare no competing interests.