An expanded framework for wildland–urban interfaces and their management

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Wildland–urban interfaces (WUIs), the juxtaposition of highly and minimally developed lands, are an increasingly prominent feature on Earth. WUIs are hotspots of environmental and ecological change that are often priority areas for planning and management. A better understanding of WUI dynamics and their role in the coupling between cities and surrounding wildlands is needed to reduce the risk of environmental hazards, ensure the continued provisioning of ecosystem services, and conserve threatened biodiversity. To fill this need, we propose an expanded framework for WUIs that not only conceptualizes these interfaces as emergent and functional components of socioecological processes but also extends them vertically from the bedrock to the top of the vegetation and horizontally across heterogeneous landscapes. This framework encourages management that reconciles pervasive trade-offs between development and resulting multiple environmental impacts. Focusing on southern California as a case study, we use the framework to facilitate integration across disciplines and between scientists and managers.

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At the juxtaposition between highly and minimally developed lands, wildland–urban interfaces (WUIs) are increasingly conspicuous features across the planet and are hotspots of rapid environmental change (Radeloff *et al*. 2018; Bento-Gonçalves and Vieira 2020; Miranda *et al*. 2020). Fire in WUIs, for instance, is responsible for ever more catastrophic health outcomes and infrastructure damage (Moritz *et al*. 2014); other hazards also prominent in WUIs include greater incidence of disease (eg Lyme disease), more frequent flooding and debris flow, and degraded air and water quality (Burke *et al*. 2013; Bytnerowicz *et al*. 2015; MacDonald *et al*. 2020). Co-occurring with elevated hazards within WUIs are the production of critical ecosystem services that span provisioning of clean water to health and economic benefits provided by recreational greenspaces (Jenerette and Larsen 2006; Porse *et al*. 2018; Garnache *et al*. 2018). The impacts of WUI dynamics on people are mirrored by increased risks to native species and ecosystems through increased habitat loss and degradation (Soulé *et al*. 1992; Bar-Massada *et al*. 2014; Park and Jenerette 2019). The risks, services, and conservation opportunities within WUIs are reciprocally influenced by urban drivers. Development transforms and fragments land cover, influences climate, increases pollution, alters disturbance regimes, and facilitates nonnative species introductions. The many bidirectional interactions between wildlands and urbanization at the interface create a coupled social and biophysical system with extensive spatial heterogeneity (Figure 1). The multiple competing roles of WUI dynamics for humans and native species underscore the need for interdisciplinary understanding of WUI dynamics and the coupling between cities and their surrounding hinterlands (Driscoll *et al*. 2016; Bento-Gonçalves and Vieira 2020).

In a nutshell:

- We propose an expanded framework for wildland–urban interface (WUI) research and management that encompasses multiple processes and varying structures that influence hazards, ecosystem services, and conservation
- WUIs and their dynamics emerge from socioecological coupling, are embedded in the vertically structured critical zone, and interact with extreme landscape heterogeneity
- Management of WUIs must emphasize trade-offs among development, multiple ecosystem processes, and stakeholders in the context of local conditions and larger government policies
- Southern California serves as a model for our framework, a region where WUIs are prominent, interact with many stakeholders, and are associated with environmental risks, critical ecosystem services, and conservation challenges

We address the need for an interdisciplinary WUI framework by expanding the original WUI focus on fire hazards (eg Radeloff *et al*. 2005; Miranda *et al*. 2020) and combining this with other frameworks that emphasize nonnative species (Park

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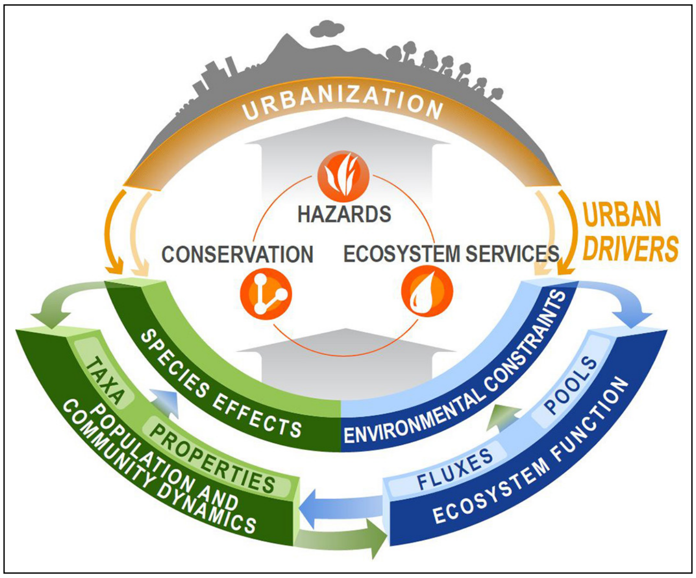

Figure 1. Wildland–urban interfaces (WUIs) result from the coupling between interactive biotic and abiotic processes, reflecting population and community dynamics as well as ecosystem functioning (green and blue arrows). Urbanization can not only influence species effects by introduction of nonnative, or removal of native, taxa but also modify environmental constraints, including altered resource availability and climate (orange arrows). Ecological system processes feed back (gray arrows) into urbanization through altered ecosystem services, hazards, and conservation risks that influence multiple diverse stakeholders.

and Jenerette 2019), wildlife (Miller and Schmitz 2019), water withdrawals (Porse *et al*. 2018), and pollution (Bytnerowitz *et al*. 2015). Recent progress characterizing individual components of WUI dynamics sets the stage for an integrative perspective that connects urban development with systems of interacting ecological and environmental dynamics extending beyond urban boundaries. Similar integrative frameworks have been directed toward the development of theories of socioecological interactions within predominantly natural landscapes (Ostrom 2009) and highly developed cities (Collins *et al*. 2011; Groffman *et al*. 2017). Linking a framework across natural and urbanized systems will help reconcile the multiple pressures and expectations that are a central challenge for WUI management.

Table 1. Building blocks for an expanded wildland–urban interface (WUI) framework

Building block	Role in WUI science
Social–ecological coupling	Urbanization is fundamentally a societal process that interacts with ecological constraints; land management reflects stakeholders and governance efforts to direct ecological system dynamics
Critical zone	WUIs extend from bedrock to the top of the vegetation and emphasize coupling between terrestrial, aquatic, and atmospheric processes
Landscape heterogeneity and connectivity	WUIs highlight contrasting landscape elements with varying adjacencies and connectivity; flows between landscape elements are critical for ecological functioning

Toward an expanded WUI framework: building blocks and integration

Providing a comprehensive definition of WUIs is challenging. Although definitions for what constitutes wildlands, urban areas, and interfaces vary widely, operational characterizations of the WUI typically involve a combination of specific spatial configurations and socioecological processes, with development and fire risks prominent (Bento-Gonçalves and Vieira 2020). Most commonly, WUIs have been described as "communities…at high risk from wildfire" (USDA 2001) and locations "where houses meet or intermingle with wildland vegetation" (Radeloff *et al*. 2005). These definitions and their intent reflect a legal establishment of the term in the context of mapping and assessing fire risks to human communities (eg Radeloff *et al*. 2018). Nevertheless, WUI definitions have been expanded to encompass multiple scales and processes (Bento-Gonçalves and Vieira 2020; Miranda *et al*. 2020). In this context, emphasis has been directed toward distinguishing true interface (where contiguous development abuts wildlands) from intermix (where more isolated patches of development are embedded within wildland habitats) areas (Radeloff *et al*. 2018). Natural habitat remnants (Soulé *et al*. 1992) constitute the converse of intermix, where wildland patches are embedded within developed areas either as isolated undeveloped lands or as riparian corridors surrounded by urbanization (Solins *et al*. 2018). Other frameworks have been similarly devised to map the locations of urban–wildland interactions, such as the footprint of urban ecosystem service withdrawals (Jenerette and Larsen 2006), extent of pollution plumes (Bytnerowicz *et al*. 2015), or distributions of conservation vulnerabilities (Franklin *et al*. 2011). This plurality of contrasting WUI types reflects the multiple dimensions of interactions in WUIs that may lead to both sharp and diffuse boundaries.

To encompass the multidimensional nature of WUIs, we propose an integrated regional framework that envisions WUIs as arising from three conceptual building blocks: (1) a social–ecological coupled system, (2) the vertical structure of the critical zone from the bedrock to the top of the vegetation, and (3) the horizontal heterogeneity and linkages across the landscape (Table 1). Each of these building blocks borrows from rapidly expanding fields that to some extent have advanced in isolation. Integration of these building blocks highlights feedbacks among development, society, ecosystem functioning, and species distributions. Together, these building blocks conceptualize feedbacks as a single dynamic system with extensive three-dimensional structure. Our framework provides opportunities for better characterizing individual regions, facilitating comparisons across regions, and managing WUIs for improving both societal and ecological well-being.

A social–ecological coupled system

Our first conceptual building block underscores the importance of social and ecological coupling (Ostrom 2009; Collins *et al*. 2011; Groffman *et al*. 2017). WUIs are emergent systems arising from the interactions between development and ecological processes. The dynamics of WUIs are principally shaped by socioeconomic and cultural drivers of development that reflect interactions among a patchwork of private and public stakeholders spanning land developers, landowners, residents, businesses, nongovernmental organizations (NGOs), and government agencies (Pincetl 1999; Fulton 2001; Press 2002). Stakeholder actions are influenced by diverse goals, jurisdictions, and capacities, and operate across multiple spatial scales, ranging from individual homeowner parcels to large landscapes. Economic drivers related to housing demand and real-estate development play large roles in directing WUI governance (Pincetl 1999). However, WUI stakeholders differ widely in their values regarding development, perceived need for services, vulnerability to hazards, and conservation (Wyburn and Bixler 2013; Driscoll *et al*. 2016). Marginalized stakeholders with limited power and elevated vulnerabilities, including people of color and people experiencing poverty or homelessness, disproportionately suffer from adverse WUI dynamics (Adams and Charnley 2020), whereas wealthier stakeholders have greater capacity for shaping development patterns and provisioning of ecosystem services for their benefit (Press 2002). With differences among stakeholders and the polycentric nature of WUI governance (Pincetl 1999), reconciling trade-offs among stakeholders is a substantial – but necessary – challenge for modeling dynamics of WUI distribution and functioning.

The vertically structured critical zone

While WUIs arise through socioecological system dynamics, they are embedded within a vertically connected critical zone, our second conceptual building block. Emerging from the ecosystem concept (Golley 1993), the critical zone is an increasingly popular framework for defining the layer of the Earth where geological, hydrological, and atmospheric processes interact with living organisms (Amundson *et al*. 2007; Minor *et al*. 2019). The critical zone approach underscores the tight vertical coupling and flows from bedrock to the top of the vegetation and built structures. Lessons from critical zone science have shown the importance of subsurface hydrologic and geomorphic processes to near-surface species distributions and ecosystem functioning (Goulden and Bales 2014). In expanding current WUI frameworks, a critical zone lens extends the focus from an historic emphasis on plant canopies and fuel loads to the coupled biotic and abiotic factors that influence species distributions; at the same time, it recognizes the additional aquatic, atmospheric, and subsurface components of the ecosystem that interact with urbanization (Minor *et al*. 2019). An explicit recognition of hydrologic connections within the critical zone (eg Jones and Holmes 1996; Amundson *et al*. 2007) enables consideration of an important feedback between water and vegetation. These connections further extend the WUI to aquatic components of the landscape, including riverine, riparian, and wetland systems, that also play important roles in shaping disturbance risk, ecosystem service provisioning, and conservation of threatened species (White and Greer 2006; Qiu *et al*. 2017; Minor *et al*. 2019). Similarly, urbanization processes influence critical zone dynamics above the land surface with strong effects on local climate, most prominently through urban heat islands, and regional atmospheric chemistry. Initially developed by geoscientists, the critical zone concept is increasingly being used for assessing feedbacks between societal and biophysical processes (Minor *et al*. 2019) and provides an integrative perspective for urban–wildland dynamics at the WUI.

Landscape heterogeneity and connectivity

As the first two building blocks highlight a socioecological coupling that extends vertically throughout the critical zone, the third building block emphasizes landscape heterogeneity and connectivity. Horizontally, the WUI features extreme spatial heterogeneity and connections between locations that may not be immediately adjacent. Within WUIs, the combination of developed and undeveloped lands leads to landscape configurations and spatial variation in resources that in turn influence disturbance regimes (Syphard *et al*. 2007), ecosystem functioning (Bytnerowicz *et al*. 2015), and species distributions (Park and Jenerette 2019) that all contribute to altered hazards, ecosystem services, and conservation. Key components of WUI boundaries are the diverse flows of matter and energy between cities and wildlands, which are influenced by multiple processes (Table 2). Flows vary in their scale and can be directional between wild and developed lands across the WUI or originate within the WUI and spread into both wild and developed lands. For example, terrestrial pollutant emissions to the atmosphere readily move laterally across the boundaries of different land covers and may influence ecological processes more than 100 km from the location of emissions (Bytnerowicz *et al*. 2015). Alternatively, wildfire smoke spreads from WUIs into adjacent wildlands and urban areas (Moritz *et al*. 2014), in some cases extending for more than 1000 km and impacting millions of urban residents. In these and other examples, landscape structure, connectivity, adjacency, and edge effects are connected with WUI dynamics.

Integrating the three WUI building blocks

Integrating a social–ecological system approach for the emergence of WUI dynamics with an extended view of the system in three dimensions throughout the critical zone and across the landscape provides a framework to

Table 2. Examples of key flows across WUIs

Flow	Main processes	Scales – spatial and temporal	Bidirectional flows	Primary drivers	Management aims
Biodiversity	Abiotic filtering; dispersal (genes, propagules, individuals); species interactions	Dependent on species' traits: from centimeters to kilometers and years to decades	Nonnative species invasions from urban and natives from wildlands	Dispersal; habitat suitability	Limit nonnative species impacts; enhance urban biodiversity; implement wildlife corridors to facilitate dispersal
Water	Precipitation; runoff; groundwater; effluent	10–100s m: ecohydrology; 1–100s km: availability and withdrawals	Urban withdrawal; effluent return	Precipitation; flow paths; engineering; upland evapotranspiration	Sustainable withdrawals; preserve in-stream uses; reduce flooding; clean effluent
Climate	Urban heat island; wildland climate effect	10s m: boundary effects; 10–100s km: regional climate modifications	Dependent on urban–wildland contrast	Sensible and latent heat changes; energy storage	Reduce effects for conservation; water supply management
Pollution	Fixed point (port); transportation; fire; biogenic	100s m: local effects; 100s km: transport	Chronic: urban to wildland; fire induced: wildland to urban	Emissions; wind; deposition velocity	Conservation and human health; reduce emissions
Fire	Ignition sources; fire spread; biomass consumption; emissions	1–10s km (small to large fires); 100s m–10s km (land-use planning); 10–100s m (fuels management near structures)	Bidirectional: urban fire into wildlands and reverse	Ignitions; wind; fire weather; fuel moisture	Minimize risk to human communities; fuel management and land-use planning; reduce human ignitions; prevent establishment of nonnative species

consider multiple processes and scales. In the framework we propose, the dynamics of the WUI (which determine its location) and the dynamics within the WUI (which determine its functioning) depend on the feedback between society and the biophysical environment. The feedback not only may be lagged in time and separated geographically, in part due to varying responses of society and the environment, but also cuts across multiple urban drivers to WUI dynamics (including development, pollution, and altered species composition) to societal responses (including hazards, ecosystem services, and conservation). This expanded WUI framework encompasses processes spanning aquatic to terrestrial habitats, private to government values, and opportunities and challenges for management across competing societal goals.

Managing WUI dynamics to achieve multiple objectives

Because WUIs emerge from coupled societal and environmental systems, people can work to improve future WUI dynamics and conditions. Nevertheless, cooperative WUI policy and management approaches need to include recognition that any individual policy or management activity will have multiple consequences (Burke *et al*. 2013; Syphard *et al*. 2016). The challenge is to identify potential indirect effects and reconcile resulting trade-offs (Driscoll *et al*. 2016). The management trade-offs of ongoing development pressures and minimizing environmental impacts are an overarching constraint influenced by diverging stakeholder perspectives and power. With increasing demand for development, the trade-offs for implementing ecological management become more problematic. Rising land prices can lead to pro-development "shadow" governments, including commissions and boards, that have an outsized influence on land-use zoning and general plans (Pincetl 1999). At the same time, many people move to WUIs for the recreation and aesthetic ecosystem services they provide, which may conflict with increasing development pressures (Fulton 2001; Garrison and Huxman 2020).

Managing WUI dynamics in the face of such pressures presents multiple challenges. Some land is deliberately conserved in the WUI through strategic environmental planning. However, WUI land conservation can also occur in response to vocal (and often wealthy) homeowner coalitions, who use such conservation as a form of growth control to preserve the amenities of the area (Fulton 2001; Pincetl 1999). In either case, decision making often takes place despite limited knowledge about critical environmental interactions and trade-offs (Stosch *et al*. 2019). As one well-documented example illustrates, fire management activities can enhance erosion, thereby reducing water quality and creating corridors for nonnative species spread (Burke *et al*. 2013). In other examples, terrestrial WUI dynamics influence water availability through changes in species and ecosystem dynamics (Goulden and Bales 2014), discharge patterns by expanding impervious surfaces (White and Greer 2006), and water quality through septic management (Withers *et al*. 2014). Given the large economic incentives for future development within WUIs, the importance of minimizing environmental impacts is equally large.

Developing WUI management tools to overcome competing pressures is challenging; policies at state and national scales are hampered in addressing issues that are predominantly localized. A constraint to comprehensive WUI management is the jurisdictional limitations across stakeholders (Qiu *et al.* 2017). Nevertheless, opportunities to overcome management hurdles are increasingly being identified and used to engage local collaboration, such as joint powers agreements and multiple species habitat conservation plans (Greer 2004; Franklin *et al.* 2011). Identifying potential synergies and trade-offs is valuable for fostering relationships of mutual trust and facilitating management that addresses multiple goals. For example, achieving species conservation objectives by purchasing private land can also be an effective strategy for reducing fire risk (Syphard *et al.* 2016). Regional land management targeting ecosystem services and habitat conservation has had success coordinating within and across sectors at regional scales (Qiu *et al.* 2017). While multi-objective, multi-stakeholder management and decision making is not unique to WUIs, these issues take on added importance in WUIs, given the diverse array of stakeholders, jurisdictions, systems of governance, and possible objectives.

Case study: southern California

We use southern California (Figure 2) as a case study to illustrate the application of an integrated WUI framework. Southern California is home to more than 23 million people largely concentrated in dense urban agglomerations. However, low-density peri- and ex-urban developments are also proliferating rapidly. The imprint of urbanization in southern California extends from the bedrock into the atmosphere, influencing groundwater, soil, land cover, climate, and air quality (Bytnerowicz *et al.* 2015; Porse *et al.* 2018; Underwood *et al.* 2018). Substantial landscape heterogeneity is prevalent in southern California, with many gradients created by urbanization, the prominent coastal to inland climate gradient, and a 3.5-km elevation gradient. The region includes extensive riparian habitats that create WUI corridors and play important roles in the well-being of both people and native plant and animal species (Figure 3). In the context of a coupled socioecological system that exhibits substantial vertical and horizontal structure, WUI dynamics in the region are strongly affected by dynamics of development interests, and potential economic benefits can have an outsized influence on decision making (Pincetl 1999). Ongoing residential development within the southern California WUI involves predominantly white and affluent people (Garrison and Huxman 2020), and these residents typically have an outsized influence on local decision making (Fulton 2001). Nevertheless, riparian and other wildland remnants embedded within cities throughout the region also include large numbers of marginalized people, including people experiencing homelessness (Meyerhoff and Kearns 2020), who have limited influence on decision making.

WUIs have extensive impacts on both people and biotic communities throughout southern California. Fire is pervasive within the WUI in both uplands and in bottomland riparian corridors. Fire ignitions are almost exclusively attributable to humans in southern California, and the highest fire frequencies occur in WUIs at intermediate housing or population density, where there is sufficient fuel to sustain fires (Syphard *et al.* 2007). Along with fires, Lyme disease occurs throughout the region and is projected to spread in the future (MacDonald *et al.* 2020). In contrast to altered risks from hazards, ecosystem services provided by WUIs in

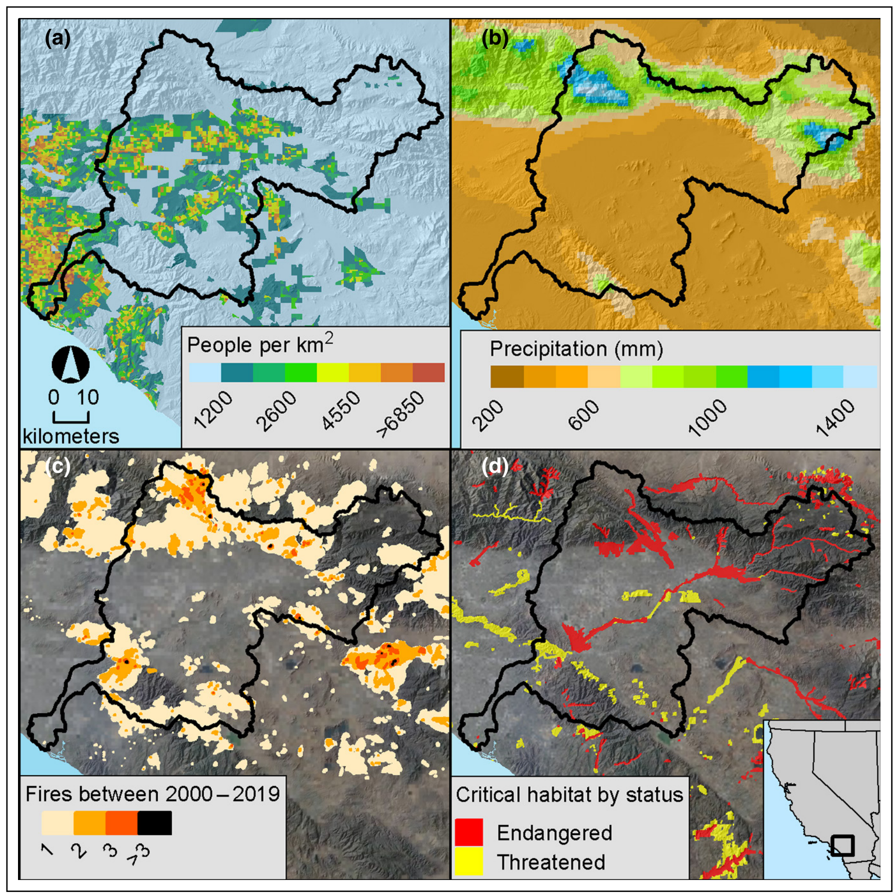

Figure 2. In southern California (black square in inset at bottom-right corner), the Santa Ana River watershed (black outline in each panel) is an illustrative example of a WUI. (a) The region features variable population densities adjacent to extensive wildlands (data from US Census; https://www.census.gov/data.html). (b) Water resources, here shown as precipitation inputs (data from PRISM Climate Group; https://www.prism.oregonstate.edu), are substantial in some areas. (c) Fire is extensive throughout the region (data from California Fire and Resource Assessment Program; https://frap.fire.ca.gov/mapping/gis-data). (d) The region is a biodiversity hotspot with extensive areas of critical habitat (data from US Fish & Wildlife Service; http://services.arcgis.com/QVENGdaPbd4LUkLV/arcgis/rest/services/USFWS_Critical_Habitat/FeatureServer).

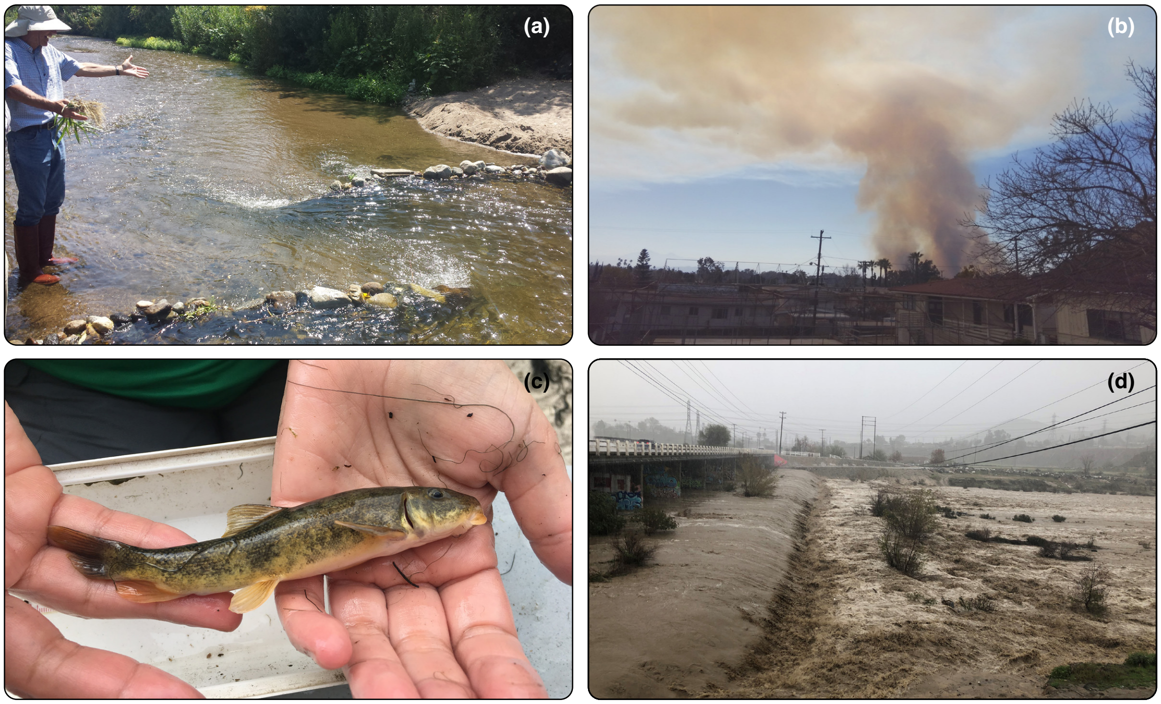

Figure 3. Ecohydrological WUI components in the Santa Ana River watershed. (a) Local resident-made structures in the active river channel, which alter hydrology and habitat for threatened species. (b) Smoke plume from riparian fire adjacent to heavily developed lands. (c) The Santa Ana sucker (*Catostomus santaanae*), a threatened fish whose extant range lies almost entirely within the WUI. (d) A large flood event, which can generate substantial water and sediment flows that affect species and societies within the floodplain. Image credits: (a) I Achimore/SAWPA, (b) K Russell/Riverside-Corona Resource Conservation District, and (c and d) P Saffarina.

southern California are highly valued. The WUI is an increasingly important source for regional water withdrawals (Porse *et al*. 2018), while also providing opportunities for recreation and cultural benefits (Garnache *et al*. 2018). These hazards and services occur in a global biodiversity hotspot, with 109 species inhabiting the terrestrial–aquatic continuum that are federally listed as endangered or threatened in five of the six counties comprising most of the region (Orange, Los Angeles, Riverside, San Bernardino, and Ventura counties); San Diego County is also a center of endangered species richness for plants, mammals, and fish (Dobson *et al*. 1997). Protecting at-risk species is important to many local residents and private organizations and is mandated by federal and state laws (Pincetl 1999).

Management actions in southern California's WUI historically have been directed toward meeting specific goals, such as reducing hazards (eg wildfire; Syphard *et al*. 2016), conserving threatened species (Press 2002), or maximizing resource provisioning (Porse *et al*. 2018), rather than holistic planning (Pincetl 1999). Fire management activities are extensive, with large federal, state, and local efforts directed toward vegetation management or fire suppression response tactics. Nevertheless, collaborative governance that includes water resource agencies, state and federal wildlife and natural resources agencies, and NGOs has also arisen in part as mandated by the California state government through the Natural Community Conservation Planning Act initiated in 1991. Although these efforts have met with modest success, they suffer from an inherent tension: namely, conservation planning is funded through development and/or highway mitigation funds, and as such conservation funding is largely dependent on development (Pincetl 1999).

Collaborations among groups allow for regional umbrella planning and "multi-beneficial" project implementation across the entirety of the region and its public and private stakeholders, while maintaining jurisdictional autonomy (Greer 2004). The success of collaborative management initiatives to generate new interactions in southern California has varied, with integrated water management an example showcasing the role of key individuals as well as funding opportunities influencing success (Hughes and Pincetl 2014). However, land-use planning also responds to specific homeowner preservation interests. For instance, open-space conservation in the Santa Monica Mountains was directed by local wealthy homeowners whose efforts led to management and the purchase of extensive lands for conservation (Fulton 2001; Press 2002). Challenges to collaborative regional conservation planning in the face of ongoing development pressures in southern California include lack of long-term funding, failure to adequately address species' needs, lack of effective monitoring, and conflict between developers and conservationists about unforeseen circumstances such as additional species requiring protected status (Greer 2004). The challenges and opportunities for managing WUI dynamics in southern California suggest that although application of an expanded framework is a starting point, additional applications in other WUI contexts are needed to improve understanding of interactions in and challenges for WUIs more generally.

Conclusion

Linking the multiple scales of biophysical and societal systems that include extensive vertical and horizontal heterogeneity into a coherent WUI framework is an important step toward enhanced management of the WUI and the connections between urbanization and wildlands. To further advance WUI research, detailed case studies that resolve locally determined social and environmental trade-offs are needed, along with synthetic approaches that improve characterization of WUIs at regional to global scales. Management of WUIs in the face of rapidly expanding development needs improved governance models and on-the-ground tools to address environmental impacts that are reflective of local context throughout the WUI landscape. Recurring wildfire catastrophes associated with the WUI both dominate the scientific literature and command public attention, but WUIs also provide critical ecosystem services and include habitats for many threatened species. As cities have become the prominent home for people, WUIs have become a key feature of human interactions with nature.

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Data Availability Statement

Empirical data were not used for this research.

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