The human–grass–fire cycle: how people and invasives co-occur to drive fire regimes

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Invasive grass species can alter fire regimes, converting native terrestrial ecosystems into non-native, grass-dominated landscapes, creating a self-reinforcing cycle of increasing fire activity and flammable grass expansion. Analyses of this phenomenon tend to focus on the ecology and geography of the grass–fire cycle independent of human activities. Yet people introduce non-native grasses to new landscapes (eg via agriculture), facilitate their spread (eg via road networks), and are a primary source of ignition (eg via debris burning). We propose a new framework for this phenomenon that explicitly recognizes the important role of anthropogenic activities in the *human*–grass–fire cycle. We review links between land use and invasive species as well as ignitions, with a particular focus on the spatial and temporal co-occurrences of these activities to show that these two drivers of wildfires are inextricable. Finally, management strategies that could mitigate impacts are discussed.

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One of the most notorious impacts of invasive grasses is the establishment of a grass–fire cycle, whereby invasive grass species alter fire regimes to the detriment of native species, favoring further invasion (D'Antonio and Vitousek 1992). Although the link between invasive grasses and fire is well described, the role of humans in facilitating this cycle is often overlooked. Yet anthropogenic ignitions, along with the introduction and spread of invasive grasses, likely play a key role in the grass–fire cycle. Understanding how people are integral in perpetuating the grass–fire cycle will guide future research directions and enhance fire and invasive species management.

In a nutshell:

- The invasive grass–fire cycle, whereby non-native grasses promote fire leading to further invasion, is often framed as an ecological process that occurs in the absence of humans
- Because people introduce invasive grasses and are a primary cause of fire ignition, invasive grasses and human ignitions likely co-occur, making these two wildfire drivers inextricable
- We outline a new human–grass–fire cycle framework and suggest research directions that directly address the role people play in perpetuating invasive grass fires
- We suggest a framework for management strategies that encourages fire and invasive species management communities to combine their knowledge and efforts to mitigate impacts

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A fire regime (that is, the pattern of fire in a region) is generally considered to be driven by three main components: ignitions, vegetation, and climate (Moritz *et al*. 2005). Conceptually, the addition of invasive grasses to new ecosystems affects the vegetation component, increasing flammable biomass and continuity of fuels (Brooks *et al*. 2004). While the mechanism of the grass–fire cycle focuses on vegetation (fuels), invasive grasses also tend to be associated with human land use, and by association human-related ignitions. Climate also drives regional fire regimes; for example, anthropogenic climate change has already increased fire risk in forests in the western US (Abatzoglou and Williams 2016) and will affect fire risk globally (Turco *et al*. 2018), and related changes in precipitation will impact fuel buildup and subsequent fire risk in grass-invaded ecosystems (Balch *et al*. 2013). However, we focus here on ignitions and vegetation because of clear evidence that their spatial and temporal co-occurrence contributes to the grass–fire cycle. Despite the recognized association of both invasive species and fire ignitions with people (D'Antonio *et al*. 2018), the human influence has rarely been considered theoretically as an integral component of the grass–fire cycle.

The grass–fire cycle is a major concern for conservation and land management agencies because wildfire and invasive species are economically costly (Calkin *et al*. 2005; Pimentel *et al*. 2005) and can have outsized ecological impacts, including landscape-scale native ecosystem loss (Ellsworth *et al*. 2014). Expansion of the wildland–urban interface is expected to increase the occurrence and extent of both invasive species and ignition sources (Bar-Massada *et al*. 2014; Radeloff *et al*. 2018), exacerbating their individual and combined economic impacts. The high ecological and economic impacts of these global change drivers and their associations with human activity underscore the necessity of developing a conceptual framework that integrates human and natural systems to help guide associated policy and management decisions.

Here we review recent advances in our understanding of how anthropogenic factors influence invasive grass fires and propose a new framework: the human–grass–fire cycle. We synthesize the independent influences of anthropogenic activities on both invasive species and fire ignitions, and suggest that the spatial and temporal co-occurrence of these factors is important in establishing a human–grass–fire cycle. We outline key gaps in knowledge about the human–grass–fire cycle and suggest that research be prioritized sequentially in three areas: first, by identifying species and ecosystems that are or may become involved in a grass–fire cycle; second, by expanding our understanding through an investigation of invasive grass fires in the context of additional fire regime drivers; and third, by applying this understanding to enhance management and restoration strategies (Table 1). Finally, we propose specific management strategies based on the human–grass–fire framework that encourage a holistic approach, combining the expertise of invasive species managers, fire managers, and human dimensions research.

The invasive grass–fire cycle: impacts across ecosystems

The invasive grass–fire cycle spans geography and species, and has been demonstrated in a wide variety of ecosystems globally. Increased flammability of fuels and altered ecosystem fuel structure can lead to changes in fire frequency, size, intensity, and severity, as well as seasonality (D'Antonio and Vitousek 1992; Brooks *et al.* 2004; Fusco *et al.* 2019). These changes vary based on the recipient ecosystem and invasive species (Pausas and Keeley 2014), with the most pronounced alterations occurring in environments where grass is not a dominant component of ecosystem structure (eg woody systems; D'Antonio 2000; but see Reed *et al.* 2005). Many invasive grasses also respond positively to fire and outcompete native species (eg Hughes and Vitousek 1993; Mahood and Balch 2019), resulting in a feedback loop.

Previous studies have shown that the grass–fire cycle is pervasive across a broad range of ecosystems. D'Antonio and Vitousek (1992) highlighted the potential for a grass–fire cycle globally, but only recently has this effect been documented empirically for multiple species. The grass–fire cycle has perhaps been most thoroughly researched in the cold deserts of the US, where the invasive annual cheatgrass (*Bromus tectorum*) has been linked to increased fire size and frequency, as well as altered fire seasonality (eg Balch *et al.* 2013; Bradley *et al.* 2018). However, invasive grasses have since been linked to shifting fire regimes in many additional US ecoregions, including cold and warm deserts; eastern temperate forests; southern semitropical systems (Fusco *et al.* 2019); Mediterranean California (Keeley and Brennan 2012); and native forests, woodlands, and shrublands in Hawaii (D'Antonio *et al.* 2000; Ellsworth *et al.* 2014).

These impacts are not limited to the US. For example, in Australia, the invasive perennial buffelgrass (*Pennisetum ciliare*) has been linked to increased fuel loads and fire severity in woodlands (Miller *et al.* 2010), and gamba grass (*Andropogon gayanus*) has been shown to increase fuel loads and fire intensity (Setterfield *et al.* 2010). Giant reed (*Arundo donax*) has invaded riparian areas in South Africa and California, raising concerns about increased fire risk (Milton 2004; Fusco *et al.* 2019), and invasive molasses grass (*Melinis minutiflora*) has been linked to increased ecosystem biomass and fire spread in the cerrado of Brazil (Rossi *et al.* 2014) and is also of concern in South Africa (Milton 2004). Despite these advances, quantitative evidence for the grass–fire cycle, particularly at the global scale, remains scarce. Identifying the scope and magnitude of the fire-related impacts of invasive grass globally should therefore be the starting point for understanding how invasive grass affects fire regimes (Table 1).

Non-native invasive plants other than grasses can also alter fire regimes (Brooks *et al.* 2004), but here we focus on the herbaceous growth form because grasses have the strongest potential – supported by substantial evidence – to markedly alter non-grass ecosystems and fire regimes. This may be largely due to their physical traits that are linked both with invasiveness and flammability, such as high surface area-to-volume ratio and specific leaf area (D'Antonio and Vitousek 1992; Mathakutha *et al.* 2019), rapid ignition and fire spread rates (Murray *et al.* 2013; Grootemaat *et al.* 2017), and rapid post-fire regrowth and re-accumulation of fine fuel biomass (D'Antonio and Vitousek 1992; Canavan *et al.* 2019). Research that identifies and documents invasive and fire traits across species is particularly important because it would enhance species risk assessments and help researchers prioritize additional species to investigate for fire impacts (Table 1).

Plant invasion follows human activity

Invasive species are defined in part by their association with people. Non-native plants are introduced both intentionally and accidently into previously unoccupied areas, including human-dominated landscapes (Figure 1, a and b; Bar-Massada *et al.* 2014), through human activities (Lehan *et al.* 2013), and their spread is often facilitated by human disturbance (Figure 1c; Vilà and Ibáñez 2011). A large majority (eg 75% in the US; Lehan *et al.* 2013) of invasive grasses have been introduced intentionally, with use for livestock forage as one primary pathway (Figure 1a; Lehan *et al.* 2013); for example, buffelgrass in Mexico and the US Southwest (Hanselka 1988) and gamba grass in Australia (Oram 1987) were originally introduced for this purpose. Cultivation as an ornamental is another common introduction pathway and invasion is prevalent at the wildland–urban interface, where developed areas overlap with areas of natural vegetation (Bar-Massada *et al.* 2014). In the southeastern US, for example, Chinese silvergrass (*Miscanthus sinensis*) remains commercially available for use in landscaping and

Table 1. Knowledge gaps and associated research priorities for furthering our understanding of the human–grass–fire cycle and potential management strategies

Knowledge gaps	Research priorities	Data needs
(1) Identifying the presence and impacts of the human–grass–fire cycle globally		
• Which invasive grasses currently contribute to a human–grass–fire cycle? • What grasses could contribute to a human–grass–fire cycle if introduced? • What is the magnitude and extent of human–grass–fire cycle impacts for each identified species and ecosystem?	• Identify all known fire-promoting invasive grasses, their extents, and impacts on fire regimes • Prioritize species for study, and enhance risk assessments by identifying plant traits linked to both flammability and invasion • Prioritize species for study, and enhance risk assessments by determining how fire effects can be predicted by the donor and recipient ecosystems • Conduct long-term research to document the full human–grass–fire cycle, and evaluate invaded ecosystem degradation and state transitions • Rank species based on fire and invasion potential to help direct management priorities	• Global repository for fire-prone species that includes distribution, fire effects, detailed plant traits, and priority ranking for research and management • Global spatiotemporal data for small- and medium-sized fire events that includes occurrence, intensity, and severity
(2) Understanding invasive grass fires in the context of multiple fire regime drivers		
• How will climate change impact human–grass–fire cycles? • How will altered ignition sources from changing land-use patterns impact human–grass–fire cycles? • What additional abiotic and biotic factors influence invasive grass fires?	• Identify ecosystems in which invasive grass fires are currently limited by climate and may become vulnerable with climate change • Identify climate-change-driven range shifts of invasive grasses into new ecosystems • Identify high-risk native ecosystems where fire regime changes would extirpate species of concern • Identify ecosystem-specific feedback mechanisms related to climate, ignition, and biotic variables • Determine specific ignition causes of invasive grass fires, and the spatial and temporal patterns of these causes to help inform management priorities	• Spatially and temporally explicit presence, absence, and abundance data for invasive grasses • Updated species distribution models for invasive grasses under changing climate and land-use scenarios • Spatially and temporally explicit ignition database that includes ignition cause and relevant fuels
(3) Enhancing science-based management and restoration options		
• How can the human–grass–fire cycle be prevented? • How can the human–grass–fire cycle be broken? • What types of education and outreach programs are effective at reducing invasive species introductions and fire ignitions?	• Identify ways to incorporate traditional ecological knowledge into current management practices • Determine the impacts of targeted grazing on invasion and fire across species and ecosystems • Identify conditions under which prescribed fires mitigate versus exacerbate invasion • Identify ecosystems that are vulnerable to invasive grass–fire cycles • Identify high-risk invasive grass species that can be prohibited from the ornamental plant trade • Determine the efficacy of existing programs in preventing ignitions and invasions, and if needed, develop new program strategies	• Spatially explicit long-term data of management efficacy, including grazing and prescribed fire • Detailed ecological community composition inventory following invasive species and fire management • Database of public programs and their ability to result in desired behavioral outcomes

Notes: Knowledge gaps were identified based on expert knowledge, and research priorities were distilled based on ways to most efficiently fill those gaps. “Data needs” refer to data that would be particularly useful in addressing these research priorities at national and global scales.

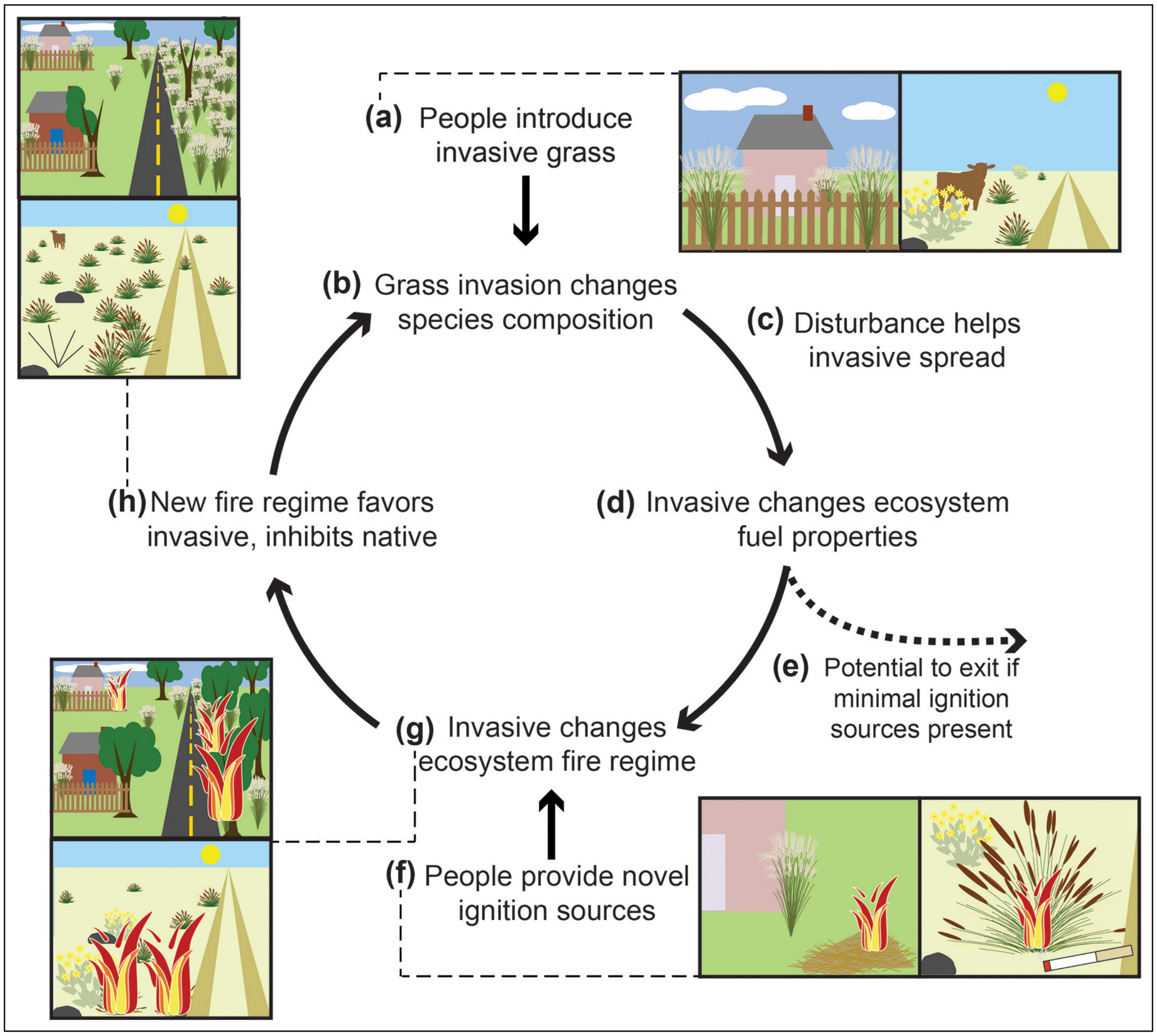

Figure 1. The introduction and spread of invasive grasses by people co-occur with human ignition pressure. (a–c) Deliberate introductions of grasses as ornamentals or forage crops coupled with human disturbance can facilitate the spread of invasive grasses. (d) Grass species act as novel fine flammable fuels, changing ecosystem structure. (e) While unlikely, exiting the human–grass–fire cycle is possible if no ignition sources are present. (f) Human ignitions are often associated with the same disturbances that aid the spread of invasive grasses (eg road maintenance), resulting in (g) shifts in fire regimes. Once the fire cycle has been altered, shortened fire-return intervals and changes in fire intensity will (h) inhibit native species re-establishment and favor invasive grass species, leading to (b) further invasion.

home gardens despite being highly invasive (Beaury *et al.* 2021).

A smaller proportion of invasive grasses have been introduced accidentally and are often associated with agriculture as contaminants in seed or livestock feed. For instance, cheatgrass is thought to have been initially introduced into Washington State and Utah as a grain contaminant originating in Europe (Mack 1981). Whether brought in intentionally or accidentally, most invasive grasses have been introduced into areas dominated by human land use (Figure 1, a–c).

Once introduced into human-dominated landscapes, invasive grasses are unintentionally spread by human activities along roads, trails, rail lines, and powerline corridors (Figure 2; Vilà and Ibáñez 2011). In the western US, grain contaminated with cheatgrass was distributed and spread along railroad corridors (Mack 1981). Many invasive grasses can establish quickly and dominate disturbed areas associated with human activities due to their rapid growth (D'Antonio and Vitousek 1992; Canavan *et al.* 2019), thereby altering ecosystem fuel structure (Figure 1d). Because humans introduce and facilitate the establishment and spread of invasive grasses, it follows that invasive grass fires will be inextricably linked to human activities.

People are a primary contributor of ignition sources

The spatial distribution of fire ignitions is driven in part by an association with humans, and anthropogenic ignition sources are an important driver of global fire regimes (Benali *et al.* 2017). For example, actively managed land uses like cropland or pasture are associated with higher fire activity at the global scale, even under meteorological conditions not conducive to fire (Benali *et al*. 2017). Indeed, human activity is such an important driver of fire regimes that it can be as or more important than climate in predicting fire activity (Syphard *et al*. 2017).

In the US, people start 84% of fires and substantially lengthen the fire season (Balch *et al*. 2017). Similar to invasive species, human-ignited wildfires are spatially correlated with human infrastructure, such as railroads, powerlines, and roads (Figure 1f; Figure 3; Fusco *et al*. 2016). Although several types of human infrastructure (eg powerlines, railroads) may themselves be ignition sources, infrastructure also provides an opportunity for other human ignitions. For example, cigarette smoking, arson, and equipment fires likely cause patterns of human ignition along road corridors (Figure 3; Prestemon *et al*. 2013; Fusco *et al*. 2016). Like roads, population density and the wildland–urban interface are also associated with the introduction and spread of invasive grasses (Figure 2), as well as human activities that cause fire ignition (eg burning of debris, smoking, arson; Bar-Massada *et al*. 2014; Fusco *et al*. 2016). However, the specific ignition causes associated with invasive grass fires remain understudied, and research in this area is necessary for understanding invasive grass fires in the context of additional fire regime drivers (Table 1). While patterns of specific ignitions are a research priority, it is clear that human activities are igniting fires in the same places that grasses invade, and in many places, it is unlikely that a grass–fire cycle would exist without human ignitions (Figure 1e).

Figure 2. Invasive grasses are most common along anthropogenic corridors and in areas with high levels of anthropogenic disturbance, features also associated with human-caused wildfires. (a) Chinese silvergrass (*Miscanthus sinensis*) growing beneath a powerline in western North Carolina, (b) buffelgrass (*Pennisetum ciliare*) near a campfire circle in southern Arizona, (c) Japanese stiltgrass (*Microstegium vimineum*) in abundance next to a city greenway in central North Carolina, and (d) cheatgrass (*Bromus tectorum*) surrounding tire tracks in northern Nevada.

Consequences and implications of the human–grass–fire cycle

Individually, invasive grasses and anthropogenic pressure can impact multiple aspects of regional fire regimes, including fire frequency, size, intensity (heat released), severity (vegetation consumed), and seasonality (Figure 1g; Brooks *et al*. 2004; Bradley *et al*. 2018; Fusco *et al*. 2019). For example, invasive grasses provide fine flammable fuels that regrow quickly, which increases fire frequency (D'Antonio and Vitousek 1992; Balch *et al*. 2013; Fusco *et al*. 2019), and human activity is associated with greater numbers of ignitions, which also increases fire frequency (Balch *et al*. 2017). Consequently, fire frequency is most likely to increase in areas where humans, human infrastructure, and invasive grasses co-occur (eg Table 2).

Unlike fire frequency, human activities and invasive grasses may have offsetting effects on fire size. Fires that burn near human infrastructure tend to be smaller, probably because they are more likely to be suppressed (Bar-Massada *et al*. 2014). However, fires in invaded landscapes could be larger due to increased fuel continuity and higher wind speeds (Freifelder *et al*. 1998; Balch *et al*. 2013; Gray *et al*. 2014). In the Great Basin, people ignite the vast majority (74.5%) of fires in areas dominated by cheatgrass and comparatively few (27.1%) in areas dominated by species other than cheatgrass (Table 2; Bradley *et al*. 2018). Although many are suppressed, ignitions in cheatgrass can lead to large fire events; for instance, the >400,000-acre Martin Fire in Nevada in 2018, which was fueled predominantly by cheatgrass, was determined to have been human caused (Short 2021). Furthermore, Balch *et al*. (2013) found that most (39 out of 50) of the largest fires in the Great Basin were associated with cheatgrass (2000–2009). Within the Great Basin, human infrastructure is relatively scarce, which may preclude high suppression efforts, but these expansive fires are still ecologically damaging (Coates *et al*. 2016) and can have negative economic impacts on grazing (Brunson and Tanaka 2011). The risk of large fires due to the presence of invasive grasses highlights the need for a renewed focus on reducing ignitions in invaded landscapes.

The combined impacts of grass invasions and human activity on fire intensity, severity, and season length may be more difficult to predict, as compared with fire frequency and size. For example, cheatgrass invasion is linked to earlier

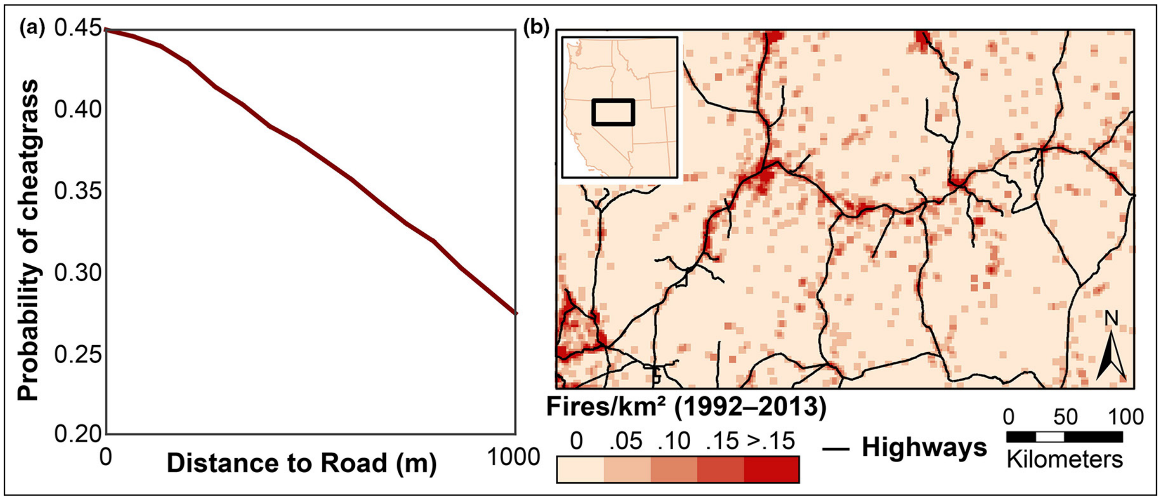

Figure 3. Co-occurrence of cheatgrass invasion and human ignitions near roads in northern Nevada. (a) Cheatgrass is more common close to roads (data from Bradley and Mustard [2006]), and (b) the density of human-started fires is highest along highways (data from Short [2015]).

season fires (Bradley *et al.* 2018), and human ignition pressure typically extends the summer fire season (Balch *et al.* 2017) well into spring and fall, when it is more likely that early- (eg cheatgrass) or late-curing (eg cogongrass [*Imperata cylindrica*]) invasive grasses will overlap temporally with an ignition source. Impacts on fire intensity and severity are difficult to interpret. Invasive grasses can be associated with both higher intensity fires (eg gamba grass; Setterfield *et al.* 2010) and lower intensity fires (eg *Bromus madritensis*; Keeley and Brennan 2012) compared to historical fire regimes. It is unlikely that people directly impact this fire regime parameter, but early and late season ignitions that coincide with less favorable fire weather may lead to more low-intensity fires.

Table 2. Proportion of fires in cheatgrass (*Bromus tectorum*) and non-cheatgrass by ignition cause category

Ignition cause	Cheatgrass fires	Non-cheatgrass fires
Lightning	25.50%	72.86%
Miscellaneous*	21.51%	8.04%
Campfire	14.12%	8.15%
Equipment use	11.83%	3.85%
Burning of debris	8.45%	2.75%
Arson	7.56%	1.66%
Fireworks	4.54%	0.51%
Powerlines	1.73%	0.46%
Smoking	1.67%	0.74%
Children	1.40%	0.46%
Railroad	1.26%	0.39%
Structure	0.43%	0.13%
Number of fires (total)	19,492	24,584
Number of fires (human)	14,521	6672

Notes: human ignitions are strongly associated with cheatgrass fires. Data from Short (2015) and Bradley *et al*. (2018). *Miscellaneous is a class of human-caused fires (eg firearm use, blasting).

An invasive grass–fire cycle can trigger prominent and rapid transformations between ecological states, the consequences of which are well documented (Figure 1h; Kerns *et al.* 2020). In many ecosystems, invasive grasses combined with high levels of anthropogenic ignition promote fire activity, resulting in altered fire regimes and ecosystem-level impacts (Ellsworth *et al.* 2014). Although conversion to an invasive grass-dominated landscape is possible without fire (Olsson *et al.* 2012), human activities and ignition sources will likely be present (Figure 1f). Once the cycle is entered, repeated or severe fires can reduce native species diversity (eg Keeley and Brennan 2012; Klinger and Brooks 2017; Mahood and Balch 2019), and it can be difficult for native species to recover even if subsequent fire is suppressed (D'Antonio *et al.* 2011). Such changes in ecosystem structure can lead to lower levels of ecosystem carbon storage (Nagy *et al.* 2020). In addition to overall reduction in biodiversity, the human–grass–fire cycle can be detrimental to culturally and ecologically important keystone species, such as the greater sage-grouse (*Centrocercus urophasianus*; Coates *et al.* 2016).

The proximity of fire-prone invasive grasses to human structures and activities also poses social and economic risks. The most destructive fires usually occur following ignition during severe wind (Abatzoglou *et al.* 2018) and are often associated with powerline ignitions (Collins *et al.* 2016). When powerline corridors are dominated by invasive grasses (eg Meyer 2003; Bradley and Mustard 2006), the increase in fine fuel facilitates the rapid spread of fire after ignition. Invasive grass fires may also cause economic losses due to their co-occurrence with livestock grazing. For example, while cheatgrass invasion has mixed effects on ranching activities, the associated increase in fire frequency can reduce forage availability following fire, with potentially negative economic impacts (Brunson and Tanaka 2011).

Mitigating human–grass–fire cycle impacts

In areas where grass invasion and fire are managed separately, strategies that integrate invasive species and fire management are essential. This approach is gaining traction in the US; for instance, the National Invasive Species Council (NISC) recognized invasive species and wildland fire as one of six priority areas in their 2020 work plan (NISC 2019). As part of this plan, NISC seeks to foster collaboration between such groups as the Wildland Fire Leadership Council and the Federal Interagency Committee for the Management of Noxious and Exotic weeds (NISC 2019).

Here, we outline management strategies that can be implemented (1) proactively (ie before a human–grass–fire cycle has been initiated), (2) reactively (ie when a human–grass–fire cycle is imminent), and (3) adaptively (ie once a human–grass–fire cycle is prevalent). We provide a framework for understanding when managers may choose to act independently, and when pooling expertise and resources will be essential for mitigating the negative ecological, social, and economic impacts of the human–grass–fire cycle.

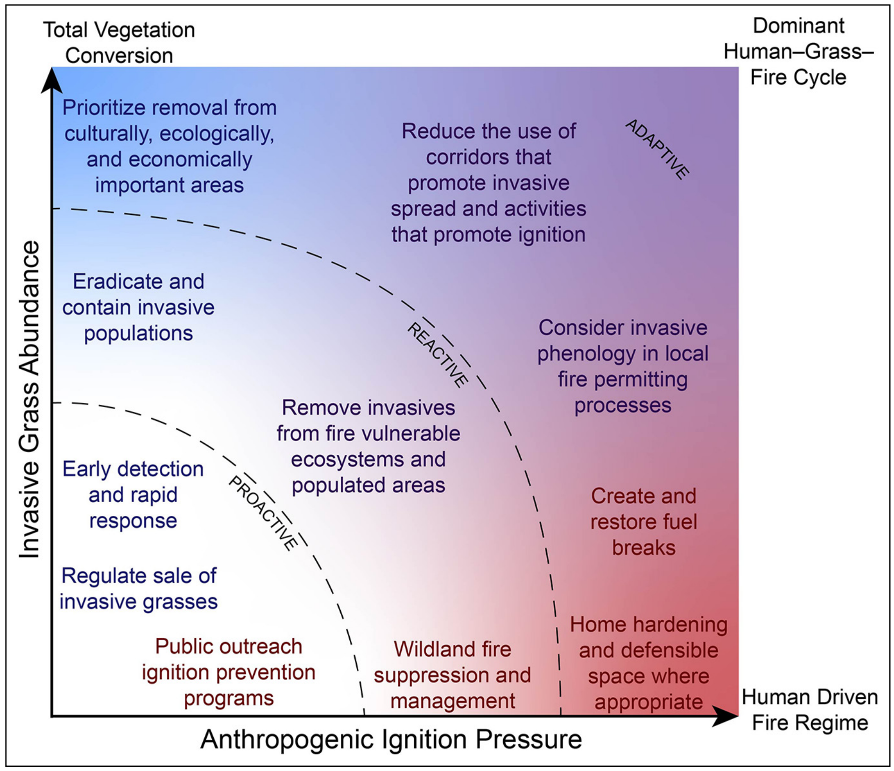

Figure 4. Proactive, reactive, and adaptive management strategies could mitigate the impacts of grass invasion and fire. As an invasion spreads (white to blue) and anthropogenic ignitions become prevalent (white to red), management strategies shift from proactive to reactive to adaptive. Examples of actions that invasive species managers will primarily work toward are shown in blue, whereas actions fire managers will enact are shown in red. Actions that may require cooperation between both management groups are shown in purple.

Proactive management strategies

Proactive management strategies are those that are implemented before fire and invasion have occurred and become problematic (Figure 4). Strategies employed at these early stages are often the most successful and cost effective (Brooks *et al.* 2004). Invasive species managers and fire managers could collaborate on strategies that identify potentially problematic fire-prone grass species before they are introduced or begin to spread widely (Table 1), or they could rank species based on their fire and invasion potential and subsequently prioritize them for further research and management (Table 1). At the proactive stage, invasive species managers could also encourage policies geared toward preventing new species introductions, discouraging landscaping that includes fire-promoting grasses, and focusing on early detection and rapid response to remove non-native grasses before they become widespread (Kerns *et al.* 2020). This will be particularly important when considering fire-prone invasive species likely to undergo range shifts under climate change (Table 1). Managers could also prioritize monitoring efforts in newly burned or critical habitat where invasive species are likely to establish, as well as reduce wildland vegetation management that creates disturbance corridors that facilitate the spread of invasive grasses. Independently, fire managers could focus efforts on public awareness campaigns and ignition prevention programs (Figure 4; Prestemon *et al.* 2013; Abt *et al.* 2015). Widespread ignitions and grass invasion tend to accompany sprawling development patterns (Bar-Massada *et al.* 2014); providing guidance and incentives for fire-smart land-use planning could help mitigate impacts (Schoennagel *et al.* 2017).

Reactive management strategies

Although proactive management strategies are often the most effective approaches, reactive management strategies can also mitigate impacts (Brooks *et al.* 2004; Schoennagel *et al.* 2017). Reactive management typically commences once invasive grasses have become problematic within the management area, but targeted efforts could control some populations. At this point, abundant ignition sources are already present (Figure 4), and reactive strategies are therefore aimed at direct control of the invasion or wildfire as a way to mitigate undesired impacts. For fire managers, such strategies may include wildland fire suppression, whereas invasion managers may focus on population-level control of the invasive species (Figure 4). For example, managers may prioritize vegetation treatments to strategic areas around communities or for safe firefighter access (Syphard *et al.* 2011), or consider mowing to remove problematic roadside vegetation. Managers may also implement targeted grazing to reduce fuel buildup, an approach that has shown promise in California grasslands (in the absence of extreme weather; Keeley *et al.* 2011). However, grazing disturbance can also promote the spread of invasive grasses (Keeley *et al.* 2011; Farrell and Gornish 2019; Williamson *et al.* 2020), exacerbating the problem. Further research is needed to determine under what conditions grazing is an effective control strategy (Table 1).

Adaptive management strategies

When invasive grasses are widespread and there is little chance of control or eradication, and human ignition sources are driving local fire regimes, adaptive strategies can be used to mitigate negative outcomes (Figure 4). These actions typically focus on altering human activities rather than directly controlling invasion and fire. For instance, fire managers could focus on campaigns that encourage homeowners to prioritize structural mitigation, including home hardening, retrofitting, and creating defensible space where appropriate (Figure 4; Schoennagel *et al.* 2017), so that homes are less likely to burn in the event of a wildfire. Once invasive grasses are widely established, fire managers may also consider land-use planning that includes strategically placed fuel breaks. However, while fuel breaks can be a useful tool for controlling fire behavior, they can also be a source of invasive grass introductions (Merriam *et al.* 2006) and therefore a concern for invasive species managers. In such cases, a focus on restoring fuel breaks with less flammable vegetation could be beneficial. Fire managers and invasive species managers could also consider invasive species' phenology when jointly determining eligibility for burn permitting. The presence of early- or late-curing grasses could make burning brush and agricultural residues in the spring or fall a higher risk, further exacerbating a grass–fire cycle. Finally, managers may opt to reduce vehicle access (eg gating entrances/enforcing off-road vehicle restrictions) in heavily invaded corridors to abate potential ignition sources.

Conclusions

Invasive grass impacts on fire regimes have been hypothesized for decades (D'Antonio and Vitousek 1992), with more recent work quantifying the broad scope of the grass–fire cycle (eg Setterfield *et al.* 2010; Balch *et al.* 2013; Fusco *et al.* 2019). However, the mechanism behind these impacts has typically been explained by the traits of invasive grasses as fuels, overlooking the importance of ignition sources in proximity to invasions. Our human–grass–fire cycle framework explicitly recognizes the importance of human activity in both the spread and ignition of invasive grasses, and suggests opportunities for invasive species and fire co-management. Changing land-use patterns, such as an expanding wildland–urban interface, will provide even more opportunities for invasive grasses and ignition sources to occupy the same space (Bar-Massada *et al.* 2014; Radeloff *et al.* 2018), likely resulting in profound changes in fire regimes. Strategies to mitigate ecological and economic impacts from these changes must focus on and remedy human-caused invasions and ignitions.

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