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Perspective

Fire needs annual grasses more than annual grasses need fire

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ABSTRACT

Sagebrush ecosystems of western North America are experiencing widespread loss and degradation by invasive annual grasses. Positive feedbacks between fire and annual grasses are often invoked to explain the rapid pace of these changes, yet annual grasses also appear capable of achieving dominance among vegetation communities that have not burned for many decades. Using a dynamic, remotely-sensed vegetation dataset in tandem with remotely-sensed fire perimeter and burn severity datasets, we examine the role of fire in transitions to and persistence of annual grass dominance in the U.S. Great Basin over the past 3 decades. Although annual grasses and wildfire are so tightly associated that one is rarely mentioned without the other, our findings reveal surprisingly widespread transformation of sagebrush ecosystems by invasive annual grasses in the absence of fire. These findings are discussed in the context of strategic management; we argue a pivot from predominantly reactive management (e.g., aggressive fire suppression and post-fire restoration in heavily-infested areas) to more proactive management (e.g., enhancing resistance and managing propagule pressure in minimally-invaded areas) is urgently needed to halt the loss of Great Basin sagebrush ecosystems.

1. Introduction

Invasive annual grasses have fundamentally altered the ecology of arid and semi-arid grasslands and shrublands of the western U.S. (Brooks et al., 2004; D'Antonio and Vitousek, 1992). Sagebrush (*Artemisia* spp.) ecosystems, in particular, have been severely impacted by invasive annual grasses including cheatgrass (*Bromus tectorum*), medusahead (*Taeniatherum caput-medusae*), red brome (*B. rubens*), ventenata (*Ventenata dubia*), and others (Mack, 1981; Young and Evans, 1970). Compared to intact sagebrush and perennial grass and forb communities, annual grass-dominated communities support lower native plant diversity (Davies, 2011; Davies and Svejcar, 2008) and diminished habitat value for sensitive sagebrush-dependent wildlife (Coates et al., 2016; Knick et al., 2003; O'Neil et al., 2020), store less carbon (Maxwell and Germino, 2022; Nagy et al., 2020), and exhibit altered inter- and intra-annual variation in primary production (Bradley and Mustard, 2005; Clinton et al., 2010).

The most conspicuous effects of these invasive grasses arise from their interaction with fire (Brooks et al., 2004; D'Antonio and Vitousek, 1992). Many sagebrush communities had sparse understories prior to invasion and burned infrequently. Historical fire rotations in Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis*) communities, for example, are estimated to have ranged from 171 to 342 years (Bukowski and Baker, 2013). Invasive annual grasses increase the amount and continuity of fine fuels in these communities, aiding ignition and spread of fire (Davies and Nafus, 2013). Consequently, fire frequency and size increase where invasive annual grasses are abundant (Balch et al., 2013; Fusco et al., 2019). Invasive annual grass abundance recovers quickly after fire, which can inhibit recovery of native perennial plants (Mazzola et al., 2011; Melgoza et al., 1990; Young and Evans, 1978). Meanwhile, keystone native shrubs such as big sagebrush (*A. tridentata*) are killed by fire and may take many decades to recolonize (Bates et al., 2020; Schlaepfer et al., 2014; Shriver et al., 2018). This positive feedback between invasive annual grasses and fire, the archetypal example of a "grass-fire cycle," promotes difficult-to-reverse vegetation type conversions (hereafter "transitions") from shrub and perennial bunchgrass and forb communities to communities dominated by introduced annual species (Brooks et al., 2004; D'Antonio and Vitousek, 1992).

Researchers and managers recognize the invasive annual grass-fire cycle as among the most urgent ecological problems facing western U.

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S. rangelands (e.g., Boyd, 2022; Coates et al., 2016; Davies et al., 2021). Among lands administered by the Bureau of Land Management, aboveground production of annual forbs and grasses has tripled in the western cold desert ecoregions since the early 1990s (Kleinhesselink et al., 2023). Smith et al. (2022) estimated that transitions to annual grass dominance affected >2300 km^2 annually across the Great Basin between 1990 and 2020. The magnitude and speed of this ecosystem transformation is such that invasive annual grasses have been identified as the primary driver of ecological degradation in the sagebrush biome over the past two decades (Doherty et al., 2022).

Less settled, however, is the degree to which transitions to annual grass dominance depend on fire. Annual plants are regarded as weak competitors against perennials in the absence of disturbance (Seabloom et al., 2003), and the competitive superiority of deep-rooted perennial grasses is central to our understanding of invasibility of sagebrush ecosystems (Chambers et al., 2016, 2007). Cheatgrass, the most widespread and abundant of the several species of invasive annual grasses, has been described as a "backseat driver" of ecological change, initially relying on a disturbance such as fire to overcome biotic resistance of native plant communities but driving ecosystem change once established (Bauer, 2012). This implies a dynamic whereby communities enter the grass-fire cycle abruptly following fire and dominance of annual grasses is maintained through repeated burning. This paradigm is pervasive, with many emphasizing the importance of fire as a driver of change (Barker et al., 2019; Mahood and Balch, 2019). The spread of annual grass dominance has been attributed to fires igniting in heavily infested communities and spreading into adjacent, intact communities (Balch et al., 2013). Several researchers, however, have noted annual grasses achieving dominance even in areas that have not burned for many years (Anderson and Inouye, 2001; Bagchi et al., 2013; Bangert and Huntly, 2010; Belnap and Phillips, 2001; Brummer et al., 2016; Germino et al., 2022). These observations suggest invasive annual grasses can overcome community resistance unaided by fire under certain conditions, raising important questions about the prevalence of transitions to annual grass dominance in the absence of fire.

The role of fire in initiating and sustaining annual grass dominance has critical implications for management of sagebrush rangelands. If transitions are rare without the catalyst of fire, a management strategy focused on targeted fire suppression and effective post-fire revegetation could effectively slow the loss and degradation of intact sagebrush ecosystems. If, on the other hand, transitions commonly proceed in the absence of fire, then ecosystem transformation by invasive annual grasses may be largely unimpeded by a fire-focused management approach. In this case, strategies motivated by principles of invasion ecology may be more effective.

We used two long-term, remote-sensing derived datasets to show that the feedback loop between invasive annual grasses and fire is markedly lopsided—fire needs annual grasses far more than annual grasses need fire. We support this contention with four observations of the role of fire in transitions to annual grass dominance in the U.S. Great Basin, a semi-arid cold desert region spanning portions of Nevada, Oregon, Idaho, California, and Utah. We show that 1) most transitions to annual grass dominance since the early 1990s have occurred unaided by recent (within the last decade) fire; 2) areas that transition following fire are typically highly invaded before burning; 3) the outcome, in terms of functional composition, is similar regardless of whether the transition was preceded by a fire, and 4) annual grass dominance is highly persistent even in the absence of fire. We conclude by discussing the implications of these observations for managing the invasive annual grass-fire cycle. These observations, which implicate invasive annual grasses themselves as a driver of ecosystem change, suggest a need for greater emphasis on proactive intervention in the invasion process.

2. Study area & methods

2.1. Study area

We analyzed transitions to annual grass dominance in the U.S. Great Basin, which we defined as the Central Basin and Range, Northern Basin and Range, and Snake River Plain ecoregions (United States Environmental Protection Agency, 2015). The analyses were masked to rangelands as defined by Reeves and Mitchell (2011), and therefore excluded cultivated and developed lands and areas where the potential natural vegetation is forest or woodlands. Additionally, we used the Cropland Data Layer (USDA National Agricultural Statistics Service, 2020) to identify and exclude recently cultivated lands included in the rangeland class in Reeves and Mitchell (2011). After masking, our study area encompassed approximately 393,000 km^2.

2.2. Datasets

We used two Landsat-derived datasets including the Monitoring Trends in Burn Severity (MTBS; Eidenshink et al., 2007) burn severity mosaics (30 m resolution) and maps of annual grass-dominated vegetation communities (30 m resolution; Smith et al., 2022) based on the Rangeland Analysis Platform (version 3; hereafter RAP) fractional cover dataset (Allred et al., 2021; Jones et al., 2018).

2.3. Mapping annual grass dominance

We used the annual, categorical vegetation maps developed by Smith et al. (2022) to identify transitions to annual grass dominance between 1994 and 2020. This approach employs *k*-means clustering to assign Great Basin shrublands and grasslands to vegetation groups based on cover of six functional types available in RAP: annual forbs and grasses, perennial forbs and grasses, shrubs, trees, litter, and bare ground. By adopting *k*-means clustering, we are acknowledging the absence of natural boundaries between communities. Rather than artificially defining boundaries, this approach focuses on identifying the centers of distinct communities or phases. Then, each pixel is assigned to the nearest cluster center in multivariate space. This data-driven approach contrasts with methods based on investigator-imposed thresholds (e.g., >20 % cover of annuals or annual cover > perennial cover), which often disregard all but one or two dimensions of the data and tend to generalize poorly.

Of the four clusters that emerged, one was characterized by high cover of annual forbs and grasses (median = 29 %), low cover of shrubs and bare ground, and a high ratio of annual to perennial herbaceous cover (median = 1.57:1); this cluster was chosen to represent annual grass dominance. The other three clusters included one predominantly composed of perennial forbs and grasses with varying amounts of shrub cover, one dominated by shrubs and bare ground, and one representing barren or nearly-barren areas (see Smith et al., 2022 for details). Pixels were assigned to clusters annually based on the temporally-smoothed cover time series (see Smith et al., 2022 for details) and transitions were defined as interannual changes in cluster membership into or out of the focal, annual grass-dominated cluster.

The dataset underlying these categorical maps has limited taxonomic resolution, distinguishing between annual and perennial herbaceous vegetation but not between native and introduced species or between grasses and forbs. We therefore looked to an auxiliary dataset to examine the composition of the annual grass-dominated cluster in greater detail and verify that these transitions were, in fact, driven by invasive annual grasses. We identified 2632 field plots from the Bureau of Land Management's Assessment, Inventory and Monitoring (AIM; Toevs et al., 2011) program visited between 2011 and 2020 that were coincident with transitions identified by our analysis and were assigned to the annual grass-dominated cluster in the year visited. We summarized species-level line-point intercept foliar cover estimates into six

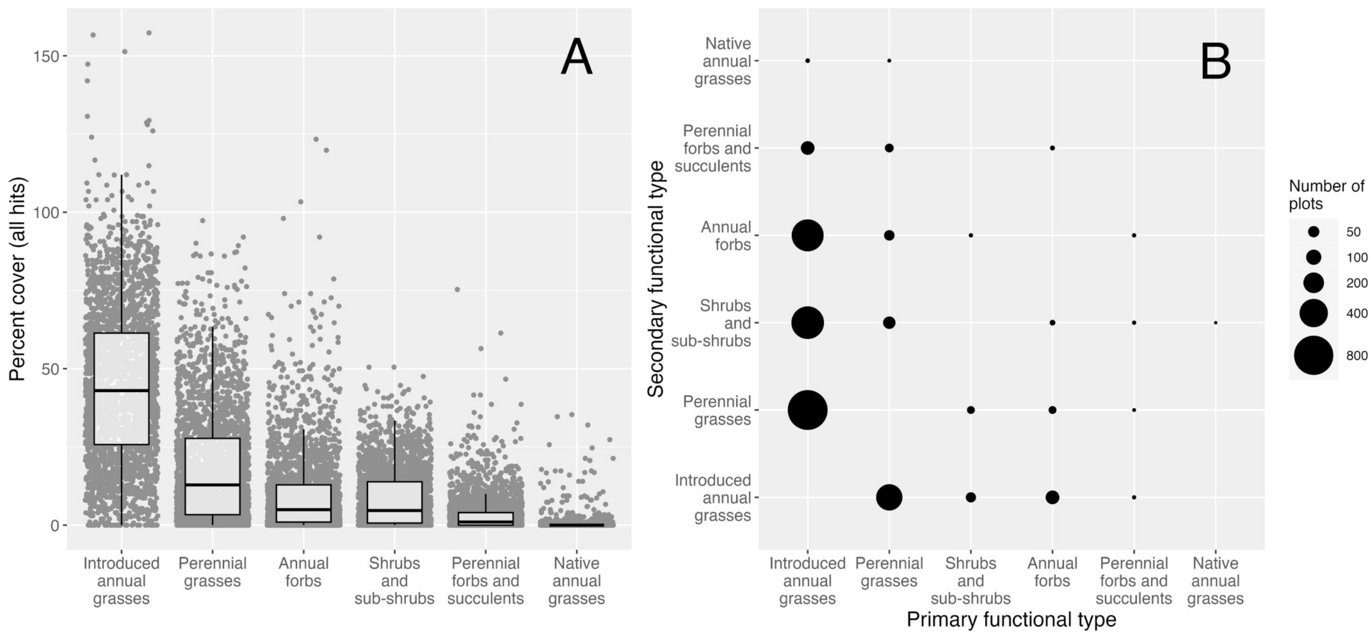

Fig. 1. Composition of pixels that transitioned to the annual grass-dominated cluster. Data are from 2632 field monitoring plots measured from 2011 to 2020 under the AIM program. Panel A shows foliar cover estimated with the line-point intercept method using all hits (total cover can sum to >100 %). Panel B shows the number of AIM plots with each combination of primary and secondary plant functional type, where primary and secondary refer to the plant functional types with the highest and second-highest cover at the plot, respectively.

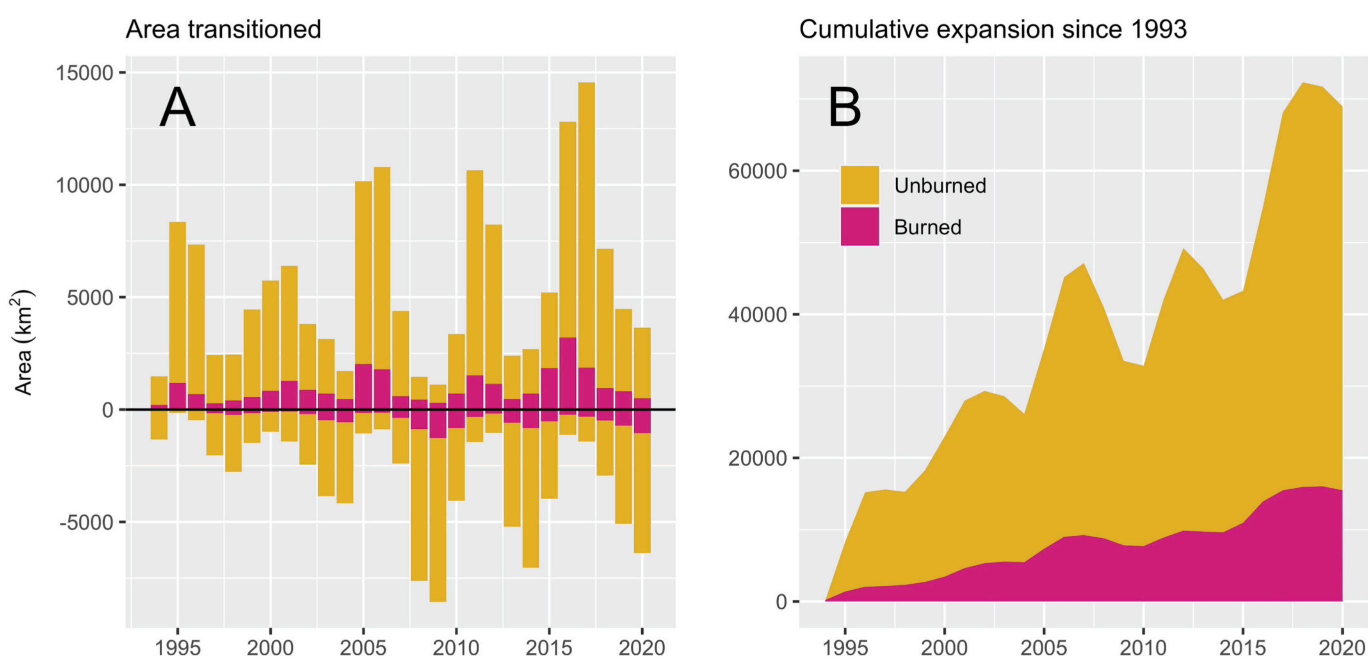

Fig. 2. Area transitioning into (above zero line) and out of (below zero line) annual grass dominance in the Great Basin (A), and the cumulative annual grass-dominated area added since 1993 in the Great Basin (B). Areas transitioning within 10 years after burning are depicted in pink, whereas areas transitioning in the absence of fire are shown in yellow. Because spatial wildfire data are incomplete prior to 1984, the 10-year fire history of transitioned pixels could only be determined for transitions occurring after 1993. Between 1994 and 2020, >66,000 km^2 transitioned to annual dominance. Of this area, approximately 77 % had not burned in the decade prior to the transition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mutually exclusive categories: shrubs and sub-shrubs, perennial grasses, perennial forbs and succulents, annual forbs, native annual grasses, and introduced annual grasses (Fig. 1).

Native annual grasses were uncommon, occurring in only 6.1 % of plots (Fig. 1). Annual forbs were common, occurring in 82.9 % of plots, but generally achieved low cover (median = 4.95 %). Introduced annual grasses were both ubiquitous and abundant, occurring in 98.6 % of plots with a median cover of 43.0 %. Furthermore, introduced annual grasses were the most abundant category by cover in 74.8 % of plots (Fig. 1). In light of these results, we are comfortable referring to this cluster as “annual grass-dominated,” and further note that the patterns reported here are driven by introduced, rather than native, annual grass species.

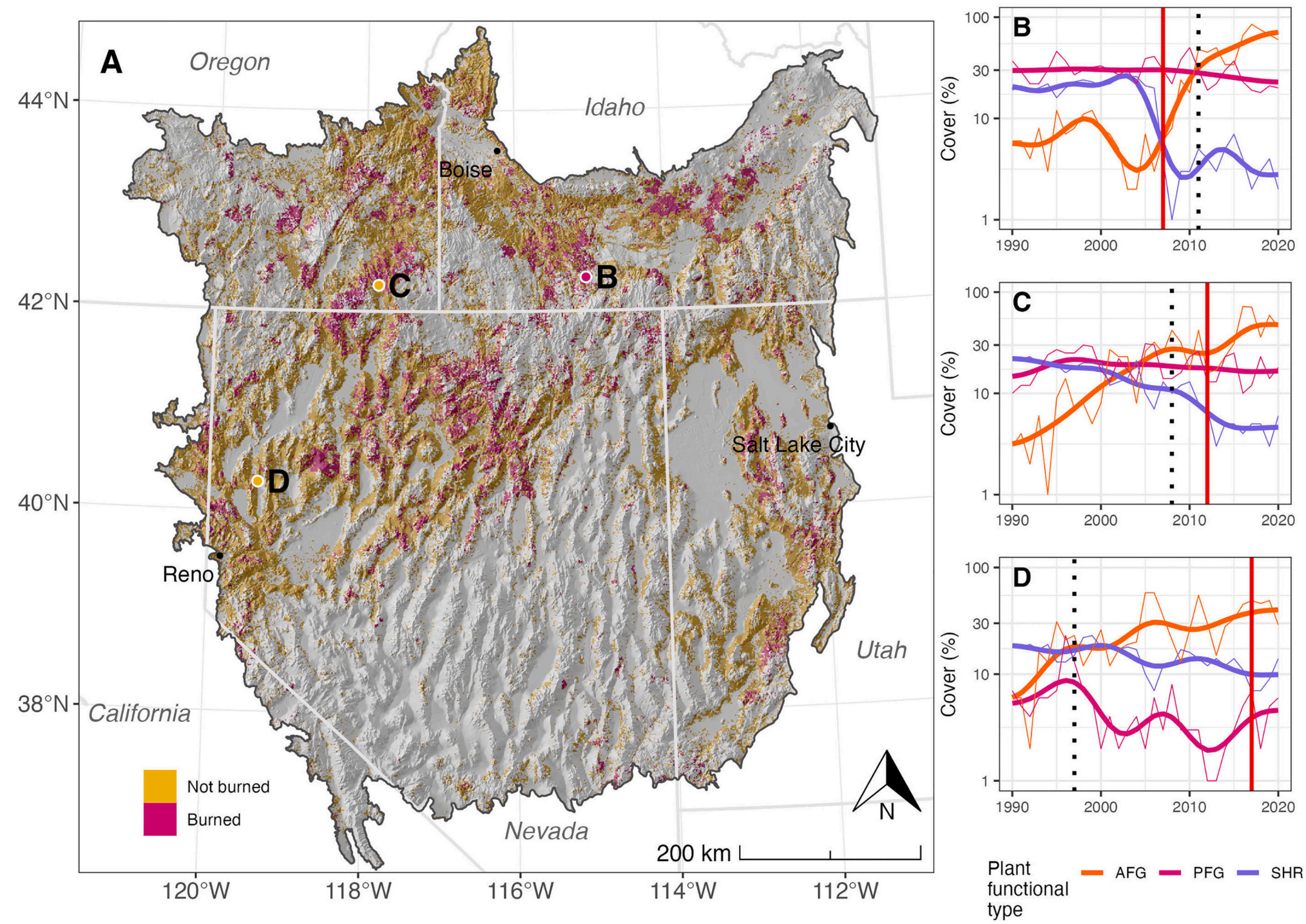

Fig. 3. Areas transitioning to annual grass dominance in the U.S. Great Basin from 1994 to 2020 (panel A, colored regions). Yellow areas transitioned without burning in the previous 10 years and pink areas transitioned within 10 years of a fire. Panels B–D correspond to the locations shown in panel A and illustrate chronologies of transitions to annual grass dominance at three representative pixels (AFG = annual forb and grass cover, PFG = perennial forb and grass cover, SHR = shrub cover). Initially high shrub cover at all three sites suggest they had not burned for many years prior to 1990. Trends are accentuated with thin plate regression splines (bold lines). Vertical lines mark the year of transition (dashed black line) and years burned (solid red lines). The transition at site B was evidently catalyzed by the 2007 Murphy Complex wildfire, which was followed by an abrupt reduction of shrub cover and increase in annual cover. Pixels C and D are examples of the more prevalent chronology, whereby steadily increasing annual cover eventually exceeds perennial cover, often coinciding with gradually declining shrub cover. Wildfires eventually affected both of these sites after annuals had achieved dominance. Note the $\log_{10}$ scale of the y-axis in panels B–D. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.4. *Temporal scale of fire effects*

We used a simple rule whereby we attributed a transition event to fire if the transitioned pixel burned at least once (according to MTBS burn severity mosaics) in the previous ten years. We chose this temporal window based on previous work indicating the maximal response of invasive annual grasses (primarily *B. tectorum*) to fire occurs within approximately five years in Wyoming big sagebrush communities (Hanna and Fulgham, 2015; Reed-Dustin et al., 2016), as well as our own analysis of post-fire vegetation dynamics across the study area using data from RAP (see Appendix 1, Supplemental Material), which supported a similar conclusion. Because the MTBS period of record begins in 1984, our analyses focus primarily on pixels that transitioned between 1994 and 2020, when a complete 10-year fire history was available.

3. Four new lines of evidence

3.1. *Most transitions have occurred without fire*

From 1994 to 2020, we estimate 87,592 km^2 of Great Basin shrublands and grasslands transitioned to annual grass dominance at least once (Figs. 2 and 3). Approximately 78 % of this area (68,627 km^2) transitioned without burning in the previous 10 years. A higher fraction of unburned transitions (62.5 %) reversed (i.e., changed to a non-annual grass-dominated state) at least once compared to burned transitions (41.4 %). Nevertheless, unburned transitions accounted for 77 % of the net expansion of annual grass dominated communities since 1994 (66,456 km^2; Fig. 2B). As of 2020, approximately 20 % of Great Basin rangelands were dominated by annual grasses (Smith et al., 2022).

3.2. *Fire catalyzes transitions already underway*

Pixels that transition after burning have nearly twice the pre-fire cover of annuals as pixels that do not transition after burning (Fig. 4). For each year from 1990 to 2010, we sampled burned pixels at a rate of 1/10,000 and recorded a) percent cover of annuals the year before burning and b) whether a transition to annual grass dominance occurred within the following 10 years. We then estimated differences in pre-fire AFG cover (natural log-transformed) among post-fire outcomes using a linear mixed effects model with year as a random effect. Mean pre-fire cover among pixels that went on to transition to annual grass

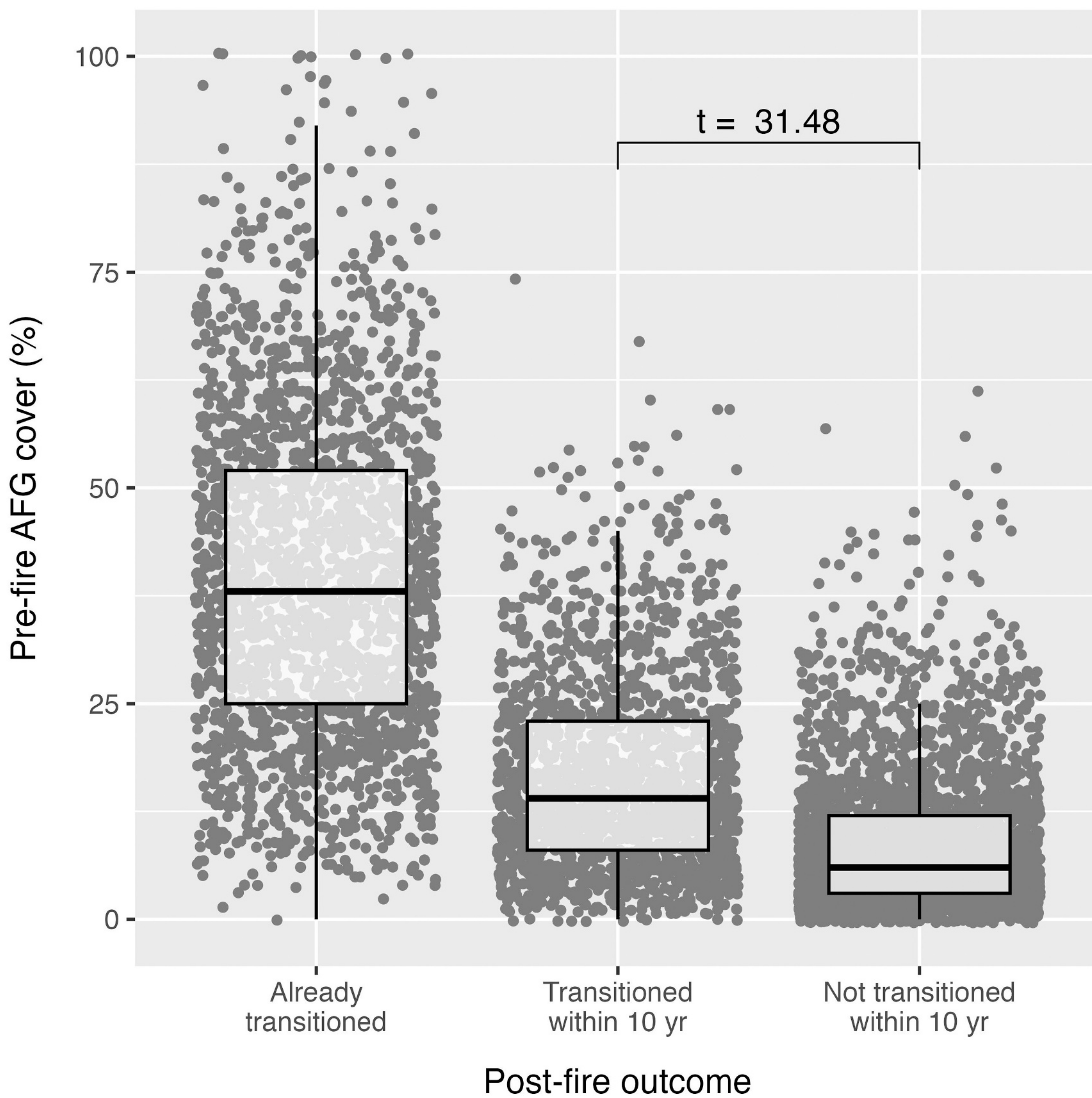

Fig. 4. Pre-fire cover of annual forbs and grasses (AFG) among regions of the U.S. Great Basin that burned in a large wildfire between 1990 and 2010, grouped by post-fire outcome. Pre-fire AFG cover among pixels that transitioned to annual grass dominance within 10 years of burning was 87.6 % (95 % CI = 80.4–95.1 %) higher than among pixels that did not transition.

dominance within 10 years (n = 1917) was 12.3 % (95 % CI = 10.9–13.9 %), whereas mean pre-fire cover was 6.6 % (95 % CI = 5.9–7.4 %) among pixels that did not transition (n = 3040; Fig. 4). This suggests fire catalyzes transitions in areas already undergoing autogenic transformation by annual grasses, but may have relatively minor effects on communities with low levels of infestation; for example, more resistant plant communities or those in unfavorable climates for invasive annual grasses.

This result aligns with previous work showing that pre-fire cover of annual grasses is highly predictive of post-fire cover of annual grasses (Barker et al., 2019), and provides further evidence that the "backseat driver" model understates the influence of invasive annual grasses as drivers of ecosystem change in their own right. This also suggests our methods may unduly credit fire as the causal agent of some transitions. A fire preceding a transition may simply hasten an outcome which would have occurred within a few years regardless of fire (e.g., Fig. S1).

3.3. Similar outcomes regardless of fire

Burned and unburned transitions involve similar changes to the dominant plant functional types. Among transitions occurring between 1996 and 2010, we calculated average cover of annual forbs and grasses, perennial forbs and grasses, and shrubs over a 21 year period spanning 10 years pre-transition to 10 years post-transition. Both types of transitions involve large increases in annual cover, an inversion of the relative cover of annual and perennial herbaceous plants (i.e., from PFG > AFG to PFG < AFG), declines in perennial cover, and declines in shrub cover (Fig. 5). Burned transitions are characterized by larger increases in annual cover and declines in shrub cover, while unburned transitions are characterized by steeper losses of perennial herbaceous cover (Fig. 5). It is important to keep in mind that these broad similarities at the scale of plant functional types may obscure important differences at the species level.

3.4. Dominance of annual grasses persists in the absence of fire

We identified 4229 km^2 that appeared as annual grass-dominated in at least three of the first five years of the time series (1990–1994) and did not burn subsequently (through 2020). Over 91 % (3879 km^2) of these unburned early-transitioned areas remained in an annual grass-dominated state at the end of the time series (i.e., were classified as annual grass-dominated in at least three years from 2016 to 2020; Fig. 6). Although persistence of annual grass dominance was slightly higher among areas that burned since transitioning, invasive annual

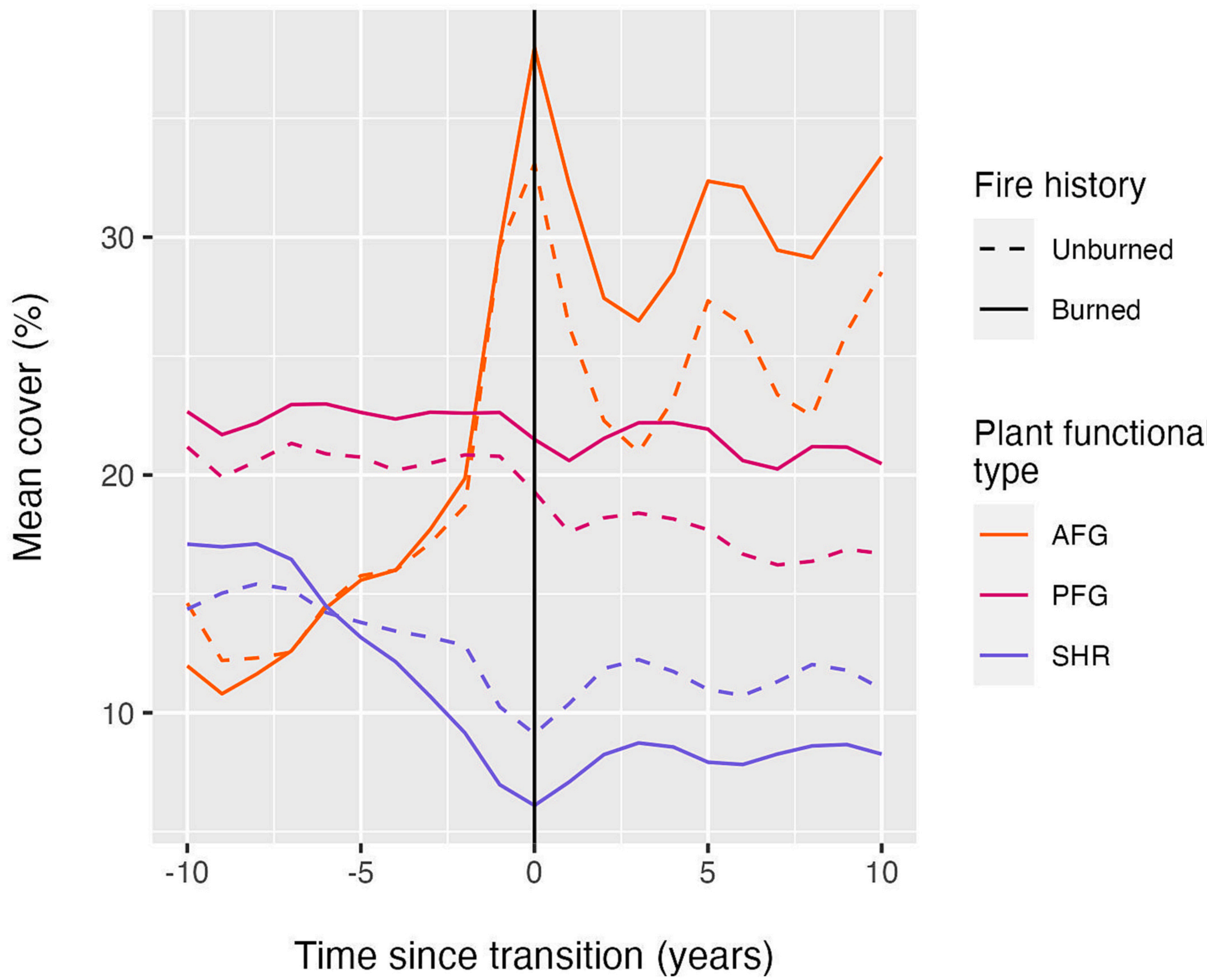

Fig. 5. Mean cover of annual forbs and grasses (AFG), perennial forbs and grasses (PFG), and shrubs (SHR) among pixels that transition to annual dominance in the Great Basin within 10 years of burning (solid line) and without the influence of fire (dashed lines). For unburned transitions that burned after transitioning, data from the post-fire period were omitted. Regardless of fire history, transitioned pixels are characterized by persistently high cover of annuals, annual cover that exceeds cover of perennials, and loss of shrub cover. Areas that transition following fire tend to have higher perennial and annual herbaceous cover and experience a more complete loss of shrubs.

grass dominance readily persists even in the absence of repeated disturbance by fire.

4. Implications

4.1. Fire is overemphasized as a driver of change

Feedbacks among invasive annual grasses, wildfire, and human land use (D'Antonio and Vitousek, 1992; Fusco et al., 2021) have seized the attention of researchers and managers working in the Great Basin—one rarely hears the phrase "invasive annual grasses" without hearing "wildfire" uttered in the same sentence. Our analyses, however, offer novel insight into the extent to which the invasion, degradation, and domination of native plant communities by annual grasses progresses independently of fire in this system.

Over time, with only sparse and discontinuous monitoring (Jones et al., 2020), the visibility of large wildfires has undoubtedly contributed to the perception of fire as the chief driver of the transformation of sagebrush ecosystems by invasive annual grasses. A wildfire provides impetus to intensively monitor vegetation recovery and a proliferation of invasive annual grasses within a recent burn scar is unlikely to go unnoticed. The post-fire emergence of an annual grass-dominated state may seem abrupt when in fact the fire delivered the *coup de grâce* to a community already past a threshold from which it was unlikely to return (Fig. S1). Whereas we might have missed—or simply failed to quantify—the gradual change before the fire, we are almost certain to notice the altered state in the aftermath.

Though perhaps the most conspicuous, wildfire is not the only disturbance facilitating invasive annual grasses. Decades of unregulated grazing by domestic livestock and feral horses around the turn of the last century contributed to the rapid early range expansion of annual grasses in the western U.S. (Knapp, 1996; Mack, 1981). Improperly managed grazing (i.e., repeated, heavy defoliation) weakens perennial bunchgrasses and trampling can damage biotic soil crusts, lowering resistance to invasion (Condon and Pyke, 2018; Reisner et al., 2013; Williamson et al., 2020). Although well-managed contemporary livestock grazing can have minimal long-term impacts on Great Basin plant communities (Copeland et al., 2021; Davies et al., 2018), growing populations of

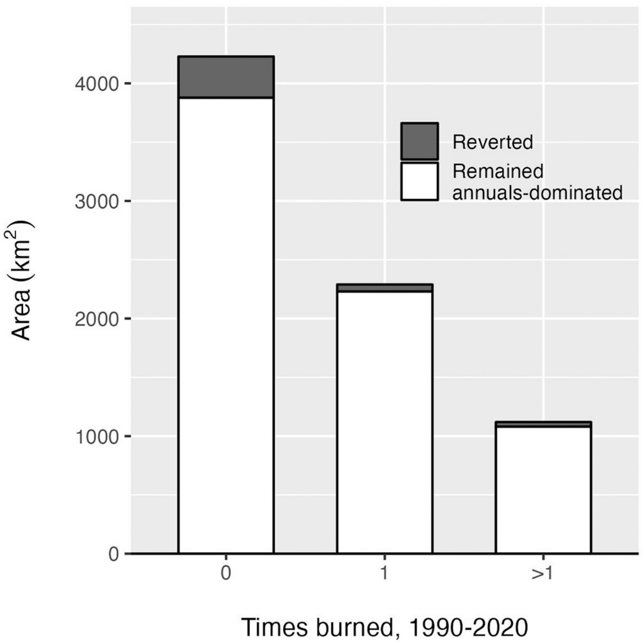

Fig. 6. Status, circa 2020, of areas dominated by annuals in the beginning of the study period (1990–1994) by burn history. Most of the area dominated by annuals in the early 1990s has not burned in large wildfires in the last 30 years. Among pixels that did not burn, >91 % remained annuals-dominated in 2020. Only a slightly higher fraction (~97 %) of pixels that burned at least once remained annuals-dominated in 2020.

unmanaged feral horses and burros co-occur alongside livestock throughout much of the region, contributing to ongoing degradation (Baur et al., 2018; Davies and Boyd, 2019; Eldridge et al., 2020). Disturbance associated with a growing human population—e.g., recreational use of public lands—may also be a contributing factor. Though sparsely populated, the Great Basin contains some of the fastest-growing urban areas in the U.S. (e.g., Salt Lake City, Utah; Boise, Idaho), and degradation by annual grasses has progressed more quickly in highly populated counties (Requena-Mullor et al., 2023). Finally, and perhaps most broadly relevant, the region's climate is rapidly changing in ways that favor annual grasses. Rising temperature, vapor pressure deficit, and atmospheric CO_2 and reduced snow cover stress native perennial plants and benefit annual grasses (Blumenthal et al., 2016; Bradley et al., 2016; Compagnoni and Adler, 2014). Spatial patterns of transitions over the last 30 years are consistent with predicted effects of these climate trends (Smith et al., 2022).

4.2. From reactive to proactive management

The overemphasis of fire as a driver of ecosystem transformation in the Great Basin has engendered a reactive management approach in which wildfire has become the de facto point of intervention in the grass-fire cycle. Implicit is the assumption that managing fire *is* managing the annual grass problem. For example, the 2013 report outlining objectives for conserving habitat for greater sage-grouse (*Centrocercus urophasianus*), a declining sagebrush obligate bird, called for managers to “immediately suppress fire in all sagebrush habitats” (USFWS, 2013). Similarly motivated by loss of sage-grouse habitat, Secretarial Order 3336 called for the development of a strategic plan to address the grass-fire cycle centered around fire prevention, fire suppression, and post-fire restoration (Jewell, 2015). The resulting reports offered a detailed roadmap for better managing fire and fire-affected lands, but were vague on the broader ecological dynamics of invasive annual grasses or strategies for managing them outside the context of fire (Rangeland Fire Task Force, 2015a, 2015b).

Given that nearly 80 % of transitions have occurred in the absence of recent fire, it is unsurprising that this paradigm has failed to meaningfully slow the degradation of these ecosystems (Doherty et al., 2022; Smith et al., 2022). While fire management plays an increasingly essential role in protecting people, infrastructure, and sagebrush ecosystems impacted by altered fire regimes (Crist, 2023), it is an incomplete solution to the annual grass problem; analogous to the mitigation of a symptom without treatment of the underlying disease. Without a commensurate investment in proactively managing invasive annual grasses among unburned sagebrush and perennial bunchgrass communities, the flammability of these communities will continue to rise (Fusco et al., 2019; Maestas et al., 2022b) and the already-unattainable goal of stopping every fire before it grows large will recede even farther from reach.

Whereas in the past it could be argued that little could be done besides putting out fires, we are rapidly acquiring the knowledge and tools to tackle invasive annuals directly. Drawing upon concepts from invasion biology and vulnerability assessment, researchers and managers across the sagebrush biome are developing strategies to scale up and reorient our efforts to manage invasive annual grasses (e.g., Creutzburg et al., 2022; Maestas et al., 2022a). Central to these strategies is a pivot from reactive restoration of heavily-impacted ecosystems toward proactive protection of relatively intact ones (Maestas et al., 2022a). Using new, dynamic, remote sensing-derived vegetation datasets (Allred et al., 2021; Pastick et al., 2021; Rigge et al., 2019), these strategies are being translated into spatial products that empower managers to deliver the right interventions in the right places.

Vulnerability of intact plant communities can be reduced by bolstering resistance to invasion or reducing exposure to invasive annual grass propagule pressure. Simultaneously depleting annual grass soil seed banks and stimulating perennial bunchgrass growth is therefore key to maintaining ecosystem services and preventing reinvasion (Monaco et al., 2017; Sebastian et al., 2017). New pre-emergent herbicides capable of suppressing annual grasses for multiple years with a single application have shown promise in early evaluations, often enhancing the growth of perennial grasses (Clark et al., 2020; Courkamp et al., 2022; Davies et al., 2023; Donaldson and Germino, 2022; Seedorf et al., 2022). Adaptations of existing management tools have also yielded promising outcomes; for example, shifting the timing of livestock grazing to fall and winter can reduce cover and density of annual grasses without negatively impacting native perennial bunchgrasses (Davies et al., 2022).

Although we are adequately equipped to get started down the right path, effective intervention will likely be highly context-dependent and substantial uncertainty remains (Schroeder et al., 2022). For example, non-target impacts of pre-emergent herbicides on native forbs have been documented (Meyer-Morey et al., 2021) and more research on effectiveness and best practices is needed, especially in the drier portions of the Great Basin. Experimentation, informed by ecological theory and local knowledge, should be supported, documented, and shared (Boyd and Svejcar, 2009). Partnerships like University of Wyoming's Institute for Managing Annual Grasses Invading Natural Ecosystems (IMAGINE; wyagresearch.org/imagine) provide a template for the kind of landscape-scale experimentation and collaboration between managers and researchers that will be key to accelerating the learning process and scaling up our successes in managing this complex and daunting ecosystem problem.

Fire will continue to be a dominant ecological driver impacting plant communities, ecosystem services derived from those communities, and the safety and economic well-being of human communities. As such, there is a long and growing list of reasons why management of fire and fuels should remain a cornerstone of efforts to conserve sagebrush ecosystems. However, our analyses make clear that managing fire is not the same as managing annual grasses, and neglecting the latter will only compound the challenges of the former. Progress on either front will require a previously unrealized, proactive effort focused on identifying vulnerable communities and acting to prevent transition to dominance by invasive annual grasses.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used in the analyses presented are publicly accessible.

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