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Evaluating the use of fire to control shrub encroachment in global drylands: A synthesis based on ecosystem service perspective

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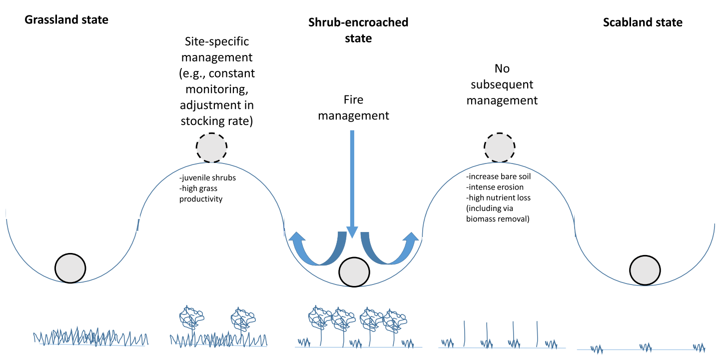
HIGHLIGHTS

- Fire managed to reduce shrub cover and density.
- Forage provisioning service in shrub-encroached lands recovered following fire.
- Yet fire could jeopardize other ecosystem services (e.g., erosion control).
- Subsequent management is the key to minimize trade-offs between ecosystem services.

GRAPHICAL ABSTRACT



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ABSTRACT

With the proliferation of woody plant species in much of the world's grasslands, human has manipulated landscape fire to return their forage provisioning service. Yet other ecosystem services (e.g., carbon sequestration, biodiversity conservation, erosion control) in the post-managed areas compared to those previously available in the shrub-encroached area are largely unknown, including trade-offs between ecosystem services. Using data from previous publications, we quantitatively synthesized the sustainability of fire as shrub management practice, expressed as its efficacy to control shrubs and its capacity to maintain different ecosystem services. A simple indicator (δ), defined as the ratio of an observed ecological attribute between area experiencing shrub management and untreated control, was used to quantify the changes. Our results showed that fire could be an effective strategy to control shrubs and to increase forage provisioning service ($\delta_{herbaceous\ biomass} = 1.39$). However, there are possible trade-offs with other ecosystem services (e.g., erosion control, nutrient cycling) when a 54% increase in bare soil cover ($\delta_{bare\ soil} = 1.54$) and ~74% loss of biological soil crusts cover ($\delta_{biological\ crust} = 0.26$) were found. Because increasing forage provisioning at the cost of other ecosystem services might not be sustainable, management should focus on strategies to minimize such trade-offs, which may include but not limited to rotational grazing, adjustment in stocking rate, or supplementary external inputs (e.g., fertilizer). Unless those measures are employed, there is possible emergence of a novel crash (i.e., vegetation- and resource-poor scabland) resulting from a combination of soil erosion and high vulnerability of burnt landscape to exotic species invasion.

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1. Introduction

Grasslands cover approximately 117 million km^2 of vegetated lands; 47% of which are located in the arid and semi-arid zone (Zhou et al., 2017). Considering the vastness of the areas that they cover (±26% of the world's terrestrial area), grasslands have considerable, multi-dimensional production as well as conservation values (Maestre et al., 2012). Since late 19th century, however, there have been changes in plant communities from grassland to shrubland in most dryland ecosystems due to the proliferation of woody plant species (Naito and Cairns, 2011). The phenomenon is often variously termed as shrub or woody 'invasion' or 'encroachment' or 'thickening' or 'proliferation', which results in significant loss in grass productivity (Scholes and Archer, 1997). Considering that increasing carbon dioxide (CO_2) and temperature are among the factors that are thought to have benefited shrubs, encroachment, including the socio-economic and environmental consequences that arise with the phenomenon, will likely persist with future climate change scenario (Caracciolo et al., 2016).

Currently grassland and shrubland are considered two stable equilibrium states (D'Odorico et al., 2012). Each state will remain in equilibrium unless it is perturbed to an intermediate condition, where it will converge to one of the two stable states (Yu and D'Odorico, 2014). Because fire is one of the main characteristics of grasslands and the distribution of most of their flora at the present has been influenced by fire (Scifres, 1980), fire is among the most important factors that can influence the bi-stable dynamics between grasslands and shrublands. By killing shrubs and affecting the rates of woody plant canopy growth, fire can sustain a significant grass cover (Brunsell et al., 2017; Case and Staver, 2017; Dew et al., 2017) and maintain grassland as a stable state of the system. Alternatively, shrubland is also a stable state of the system because of their ability to suppress grasses (Yu and D'Odorico, 2014). Shrubs are able to exploit soil water resources both under and between-canopy areas as well as to limit light availability for herbaceous species (Yu and D'Odorico, 2014). Once established, the superior ability of shrubs to withstand drought, fire, salinity and frost (Richmond and Chinnock, 1994; Booth et al., 1996) as well as disturbance such as ploughing (Daryanto and Eldridge, 2010) allow them to remain dominant.

As livestock grazing is the most widespread land use in grasslands (Maestre et al., 2017), human will continue to manipulate landscape fires and influence the fire-vegetation feedbacks. As grass cover decreases with woody plant encroachment, fire management is used under the assumption that it can reverse, prevent and manage undesirable woody species (Freeman et al., 2017). Prescribed fire has been widely applied to control shrub encroachment in the Great Plains and western United States since 1940 (Browning and Archer, 2011). It has also been recommended in Africa to maintain the co-existence of trees and grasses in savannas with mean annual precipitation >650 mm (Sankaran et al., 2005). So far, the success of fire management largely depends on its ability to kill juvenile shrubs (Ditomaso et al., 2006) and therefore, fire is, at times, used in combination with other control methods such as slashing or chemicals or the application of repeated or sequential fires (Ditomaso et al., 2006). While fire usually needs to be repeated for it to be successful, changes of vegetation state carry inevitable consequences to the whole ecosystem processes and services. Frequent fire (i.e., annual or biennial), for example, produces homogenous young shrubs which are not beneficial from conservation point of view (Davis et al., 2016). There is also increasing evidence that frequent fire may lead to the domination by exotic aliens (Sheley et al., 2008; Masocha et al., 2011).

Despite ongoing debate on its ecology, prescribe fire is still the most widely used approach for managing savannas (Masocha et al., 2011). As the cost of fire is lower than that of other control methods (e.g., chemical or mechanical), using fire to control shrubs and presumably return the forage provisioning service of grasslands will continue. From conservation point of view, such intervention aimed at reducing the cover woody species is a legitimate misuse of management which discredits conservation-oriented objectives. A large body of works suggested that shrubs-encroached areas maintain multiple ecosystem services (e.g., carbon or C sequestration, nutrient cycling, biodiversity conservation) that are associated with a well-functioning ecosystem (Archer, 2010; Barger et al., 2011; Eldridge et al., 2011). Yet millions of people, particularly in Africa, whose livelihood depends on grazing are adversely impacted by shrub encroachment (Belayneh and Tessema, 2017). Currently pastoralism and adverse environmental conditions associated with grazing have been under increasing scrutiny from greater awareness of overusing arid lands (Curry and Hacker, 1990). The whole pastoral industry thus needs to embrace shrub management as a method to achieve sustainable land-use. From management point of view, sustainability has intertwined ecological component (expressed as multiple ecosystems services), as well as social and economic components (expressed as the efficacy of shrub control method and presumably forage provisioning service) (Archer and Predick, 2014). With a positive relationship between the cover of vascular plants (including shrubs) and key ecosystem functions and services (Eldridge et al., 2011), it is very likely that there will be trade-offs between different ecosystem services (e.g., when shrubs are removed for forage provisioning service versus when shrubs are maintained) (e.g., for C sequestration or biodiversity conservation). Currently the extent of trade-offs in the post-managed areas compared to that previously available in the shrub-encroached area is largely unknown, as it is acknowledged by Archer and Predick (2014). In this research, we aim to quantitatively measure different ecosystem services in areas managed by fire and potential trade-offs among those services in global drylands. By using data from global field observations, this research will provide, not only a comprehensive perspective on how to sustainably managed grasslands that are currently under competing land-use objectives, but also an accompaniment to previously modeled fire-managed shrublands (Teague et al., 2015).

2. Methods

Published articles indexed in Web of Science from 1960 to 2018 were used to collect data on ecosystem services in shrub-encroached area experiencing burning using the following keywords: (i) arid or semi-arid or savanna or steppe or dryland, and (ii) shrub or bush or brush and (iii) fire or burning, resulting in a total of 560 articles. To ensure that the data came from the same climatic region (i.e., arid, semi-arid or drylands), we used the same annual rainfall criteria (<850 mm) as Eldridge et al. (2011). We further screened our data collection to the results of field study (not modelling or simulation). Since we wanted our data to be as representative as possible to the condition of the whole burned and unburned plots, studies that evaluated any response variables considered at the microsite level (e.g. comparing the effects of shrub vs. grass canopies on vegetation or soil attributes within the same site) were averaged across microsites (Eldridge et al., 2011).

The sustainability of fire management was assessed based on its efficacy to control shrubs, as well as the ecosystem services of post-managed shrublands. Shrub density and shrub canopy cover data were collected to measure the efficacy of fire management. Meanwhile, the following parameters (each of was analyzed separately) were collected to represent different ecosystem services: (i) herbaceous biomass and cover, (ii) bare soil, (iii) litter cover (iv) herbaceous species richness, (v) soil nutrients (0–10 cm), and (vi) soil organic C (SOC) (0–10 cm). Both herbaceous biomass and cover were observed to represent forage provisioning service, while herbaceous species richness was observed to represent biodiversity conservation service. Different regulating and supporting services, as well as their associated parameters are listed as follows: belowground C sequestration service was represented by SOC; nutrient cycling service by soil nutrients, litter and biological soil cover (Tongway, 1995; Jobbágy and Jackson, 2001); erosion control service by bare soil, litter, and biological soil cover