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Vegetation responses and trade-offs with soil-related ecosystem services after shrub removal: A meta-analysis

Running title: Ecosystem services after shrub removal

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Abstract

Aim: To assess the sustainability of different shrub control practices (fire, mechanical, and chemical), based on their efficacy to control shrubs and their effects on multiple ecosystem service provisions, including possible trade-off and/or synergy.

Methods: Using a meta-analysis approach, this study synthesized results from global shrub removal experiments. Log response ratio (*lnR*) between the outcome of shrub removal and that of the untreated control was used to estimate proportional changes in soil and vegetation properties resulting from each shrub control practice.

Results: When forage provisioning is the only service considered, shrub removal could achieve this desirable outcome as indicated by increasing herbaceous biomass. However, observable decreases in litter, biological crust cover, and soil nutrients, as well as increases in bare soil indicated long-term potential trade-offs with other ecosystem services (e.g., erosion control service, nutrient cycling); the degree may be influenced by different shrub control methods. Synergistic properties were probably limited to a short-term boost of herb productivity resulting from short-term increase in herb biomass and diversity as well as nutrient availability.

Conclusion: Human-induced drivers manifested in shrub control practices may change vegetation response. However, management also changed non-targeted processes, generating potential reduction in several regulating ecosystem services. Continuous monitoring to assess landscape conditions should therefore become the key for adaptive management. Sustainable forage production should focus on strategies to maintain multiple ecosystem services because consideration of those services can lead to long-term protection of the landscape and provide a broader range of environmental benefits.

Keywords: burning, chemical shrub removal, fire, grassland, herbicide, mechanical shrub removal

Introduction

Semi-arid landscapes are typically characterized by low annual precipitation (i.e., ranged between 200-850 mm, with median of 400 mm; Eldridge et al., 2011), long dry spells and frequent water scarcity (Wang et al., 2012). Due to a prevalent divergence in the patterns of atmospheric circulation, arid regions are mostly distributed in the 30° latitude, north and south. They comprise approximately 40% of the Earth's land surface and provide considerable, multi-dimensional ecosystem services (Maestre et al., 2012; Wang et al., 2012). Since the late 19th century, most dryland ecosystems have experienced changes in plant community structure from grassland to shrubland due to the proliferation of woody plant species (Archer et al., 2017). Because shrub encroachment is also accompanied by increases in bare surface soils and consequently declines in soil functions (i.e., changes in the spatial distribution of resources which prevent grassland recovery), the phenomenon leads to the desertification paradigm in the semi-arid regions (Eldridge et al., 2011). Since grazing is the most widespread land-use in most semi-arid ecosystems, particularly in Australia, western United States and Africa, shrub encroachment is often considered a sign of degradation due to reduction in pastoral productivity (Maestre et al., 2017). Shrub removal is therefore a common attempt to return forage provisioning service in shrub-encroached lands using a single or a combination of practices (mechanical, biological, fire, chemical).

Synthesized evidence, however, indicates that shrub encroachment is associated with increases in root biomass, total and organic soil carbon (C) and total soil nitrogen (N) (Eldridge et al., 2011), which are beneficial to maintaining soil quality in arid regions. Removal of woody plants may therefore be deleterious to soil-related ecosystem functions such as preservation of soil physical and chemical properties (Daryanto et al., 2012; Ludwig et al., 2004), as well as organic matter input via C and N fixation (Barger et al., 2011; Lajtha & Schlesinger, 1986). Partly due to the legacy effects of grazing as well as the fact that recovery after disturbance in arid environments is a slow process (Archer et al., 2017), trade-offs between forage provisioning and other ecosystem services (e.g., C sequestration) are expected with changes in the abundance of woody plants through shrub removal practice (Daryanto et al., 2013).

With increasing scrutiny from the general public due to greater awareness of overusing arid lands (Curry & Hacker, 1990), consideration of multiple ecosystem services in rangeland has been promoted to improve the sustainability of shrub management (Reed et al., 2015). While there is a significant body of literature that studies the ecosystem services in either grasslands or shrublands (Archer, 2010; Barger et al., 2011; Eldridge et al., 2011), surprisingly, there has not yet any study that focused on the ecosystem services of shrub-encroached lands after shrub removal (but see Archer and Predick (2014) and Archer et al. (2017)). To fill the knowledge gap, this study aims to provide a synthesis as to how different shrub removal methods altered the remaining biotic forces and abiotic conditions as well as processes that contribute to forage provisioning and soil-related ecosystem services, including potential trade-offs and/or synergies.

Methods

We used published articles indexed in Web of Science from 1960 to 2018 to collect data on ecosystem attributes in shrub-encroached areas experiencing burning, chemical and mechanical shrub removal as a one-time shrub removal practice. Mechanical shrub removal included all treatments that use machineries to remove shrubs, ranging from cutting, grubbing, ploughing, bulldozing to chaining, while chemical treatment involved all types of herbicides that were used to control shrubs, either sprayed or distributed aerially. Practices that repeat the use of the same treatment or include a combination of two or more practices were categorized as ‘multiple treatment’ category. Biological control (i.e., insect) was not included due to the different nature of the treatment (e.g., does not generate abrupt changes in soil ecosystem functioning) (Howarth, 1991). Biological control agents instead weaken the target plants until they are killed or become noncompetitive to other organisms (Brock, 1988).

Data collection was restricted to the results of paired field study (not modelling or simulation) in drylands (rainfall <850 mm) (Eldridge et al., 2011). Distribution of the study locations is available on Figure 1. All data were considered at least at the plot level and therefore to avoid the confounding effects of microsites (e.g., under the shrubs vs in the interspace), any response variables considered at microsite level were averaged to represent the treated and untreated plots. Because we used paired treated and treated plots over the same period of time, studies that used initial condition as control could not be included. A total of 110 articles were used to collect the database for this synthesis. The list of articles is available on Appendix 1 in Supporting Information.

Different vegetation and soil parameters (each was analyzed separately), including: (i) shrub density, (ii) shrub cover, (iii) herbaceous biomass, (iv) herbaceous cover, (v) herbaceous species richness, (vi) bare soil, (vii) litter cover (viii) soil nutrients, (ix) soil organic C (SOC) and (x) biological crust cover (BCC), were collected either to represent the efficacy of shrub management or to act as a proxy for different ecosystem services. Although these parameters are considered the most commonly recorded parameters in shrub removal experiments, they may not necessarily represent the whole spectrum of ecosystem services. We therefore limited our discussion to the indices and how they might affect the ecosystem service that they represented. Herbaceous biomass, cover and diversity were observed to represent the forage provisioning service (Archer et al., 2017). Different regulating services, as well as parameters, are listed as follows: the belowground C sequestration service is represented by soil organic C; nutrient cycling service by soil nutrients, litter and BCC

(Jobbágy & Jackson, 2001); erosion control service by bare soil, litter, and BCC (Tongway, 1995). Because different shrub management generated different degrees of disturbance to the soil, we collected soil property data as they were available in the original article. For example, observations of soil properties for fire treatment focus on topsoil only (0-10 cm) because the deeper soil layers are usually well insulated and largely unaffected by fire (Torres et al., 2012). In contrast, mechanical shrub removal that involves ploughing usually generates disturbance to the deeper soil layer and therefore the data reported changes from deeper soil layer (up to 30 cm).

Data from each article were extracted using the following procedures. If a study examined the effect of different treatments within a category of shrub management (e.g., different fire season or intensity for fire management, or different herbicide rate for chemical management), the data (the number of observation or *n*) were treated as separate contributions (Daryanto et al., 2016; Lu et al., 2016). The sample number is reported in each figure. We decided not to include grazing as a categorical variable due to the its long-term legacy effect (i.e., decades) (Archer et al., 2017), beyond the duration of most of shrub removal observations. We, however, categorized our data based on duration since treatment: short-term (≤ 5 years) and longer term (> 5 years) to assist our understanding of the successional processes after shrub removal, except for ‘multiple treatment’ data due to the difficulties in determining duration since treatment. Data from several seasons or years of observation were averaged and considered as a single data entry following Eldridge et al. (2011) to avoid over-representation of any particular study and to reduce publication bias (Lu et al., 2016). We, however, treated studies that were conducted over an extensive area as separate contributions because they often had different edaphic conditions or weather patterns (e.g., elevation, slope, or soil texture), and sometimes involved different treatments (e.g., Bates et al., 2014; Miller et al., 2014; Morton & Melgoza, 1991). While the overall heterogeneity in effect sizes may be reduced by this approach as the results are not totally independent from each other, exclusion of these results can underestimate effect sizes (Gurevitch & Hedges 1999; Karst et al., 2008).

We took a meta-analysis approach to construct the confidence intervals for each shrub control method; all tests were performed using the statistical software MetaWin 2.0 (Rosenberg et al., 2000). To accommodate the inclusion of as many sites and regions as possible, including those that did not report measurement error, unweighted analysis using the log response ratio (*lnR*) was selected to calculate bootstrapped confidence limits (Eldridge et al., 2011). Since ratio is more affected by the denominator, using *R* instead of *lnR* can generate disproportional rather than equal changes in either the numerator or denominator, especially when the denominator is small. Using *lnR* thus allows a more normal distribution of samples for small sample size and minimizes the variability that accompanied certain management such as the diversity of species, climate and soil properties, unknown presence of livestock, sometimes in combination with wildlife during successional process (Hedges et al., 1999) and ascertained that the observed ecosystem attributes at each study was due to the effects of shrub control treatment. Because response ratios cannot be calculated for a quantified variable with a zero value, we excluded comparisons that had zero values for either treatment or control.

Bootstrapping was iterated 9999 times to improve the probability that the confidence interval was calculated around the cumulative mean effect size for each categorical variable (Daryanto et al., 2016). The result of shrub control treatment is considered statistically significant if the 95% confidence interval (CI) does not overlap zero, while the difference between categorical variables (i.e., between short-term and longer term effects of shrub removal) is considered significant if the bootstrap CI intervals do not overlap with each other (Curtis & Wang, 1998; Daryanto et al., 2016; Lu et al., 2016). Statistical significance was determined at $P < 0.05$. We tested the null hypothesis that all effect sizes were equal, based on the Cochran statistic Q, with larger values indicating greater heterogeneity in effect sizes among comparisons (Rosenberg et al., 2000). Since this hypothesis was rejected and most of the parameters showed low heterogeneity, we examined the categorical variable (i.e., duration since treatment) using fixed model (Karst et al., 2008). Between-studies variance, T^2, and heterogeneity quantification indices (I^2 and H^2) are available on Table S1 (Appendix 2 of Supporting Information).

Results

Herbaceous responses

Our results showed that herb responses to different shrub removal methods were, in general, short-lived (Fig. 2). For example, the positive effects of fire on herb biomass and herb diversity (56% and 10% increases for biomass and diversity, respectively) became insignificant compared to the untreated control after 5 years (Fig. 2a). The same response was also found for chemical treatment, except for herb diversity, in which the effect was quite lasting (Fig. 2c). There was no effect of both fire and chemical treatment on herb cover, even within 5 years following either treatment. Stronger responses were found in areas managed with mechanical shrub removal, in which they had significant increases in herb cover, biomass and diversity; the effects were quite lasting in each case (Fig. 2b).

Shrub responses

Regardless of shrub control method, shrub cover and density showed a similar pattern, with significant reduction following treatment, but rapid recovery after that (Fig. 3). Mechanical shrub removal exhibited the fastest shrub cover recovery compared to the use of fire or herbicide. Although shrub cover was initially reduced compared to the untreated control, insignificant difference was observed between short- and long-term for mechanical removal, while fire and herbicide still showed a significant shrub cover reduction effect after 5 years. It should be noted, however, that there was high heterogeneity in shrub cover (Appendix 2 of Supporting Information), which might result from differences in shrub canopy architecture. Shrub density managed using mechanical shrub removal had no significant effect compared to the untreated control even five years after treatment (Fig. 3b). In contrast, chemical shrub treatment resulted in shrub cover and density reduction even 5 years after treatment (Fig. 3c).

Soil responses

Our results on soil and ecosystem response following chemical shrub removal were greatly restricted by data availability, except for non-significant short-term changes in bare soil (i.e., CI overlapped zero) between treated and untreated control (data not shown). But for response following fire, the landscape was characterized by an almost total loss of BCC (-97%) and litter cover (-82%), and a significant increase in bare soil (40%). A short boost of soil nutrients was observed (43%) immediately following fire, but the difference became insignificant after 5 years. Surprisingly, there was no change in SOC content between fire and no-fire treatments over both shorter and longer term (Fig. 4a).

Mechanical shrub removal produced similar results, except that there was an initial increase in litter cover (77%) and a reduction of bare soil (-18%). In this treatment, however, these changes became insignificant after five years. The reduction in BCC did not recover after five years. There was no effect of mechanical shrub removal on SOC, even over longer term, similar to our findings on fire management. Soil nutrient response also showed an initial boost (19%), but became quickly depleted within 5 years (-14%) (Fig. 4b).

Discussion

Changes in forage provisioning service following shrub removal

In general, we could expect an increase in forage provisioning service associated with the increase in herb biomass and to a lesser extent, cover and diversity, with slight variability between shrub removal methods (Fig. 2). These results indicated a strong initial management effect in determining vegetation response. As water and light become more available (Yu & D'Odorico, 2014), removal of shrubs allows diverse grass species to re-establish, which synergistically boosts productivity. Increases in herbaceous productivity are also supported by increases in nutrient pulses after mechanical shrub removal (Fig. 4b), as decomposition and photodegradation of plant debris occur (Gliksman et al., 2016). Similar response is found with mineralization of soil organic matter after fire (Blank et al., 2017), which also re-distributes the previously concentrated nutrients (i.e., ‘fertile island’) (Ravi et al., 2009).

Determining long-term trajectory of forage provisioning service, however, would be more challenging given the multiple factors that influence the process, among them the return of shrubs following removal. Findings from Archer et al. (2017) indicated that herb long-term survival negatively corresponds with the recovery of shrubs. Although we could achieve the desirable effects on woody vegetation (i.e., shrub cover and density reduction), such effects tended to be short-lived (Fig. 3). Because shrubs are dominated by C_3 species, steady increase in global carbon dioxide (CO_2) level accelerates juvenile growth and minimizes the time during which shrubs are vulnerable to disturbance (Bond & Midgley, 2000). Even with fire, supposedly the most effective method to control shrub (DiTomaso et al., 2006), the return of shrub cover was observed after 5 years (Fig. 3a), corresponding to reduced herbaceous biomass and diversity (Fig. 2a). In contrast, temporary reduction in woody cover is also not always followed by increases in herbaceous productivity. In area with low mean annual precipitation (~250 mm), the use of herbicides that kills plant rooting systems (Brock et al., 2014; Scifres, 1980) could be responsible to a more lasting effect of herbicide on shrubs (Fig. 3c). Its persistence in the soil could further retard shrubs that germinate from soil seedbank (Hunter et al., 1978). Yet low number of remnant native grasses and inadequate seed source can inhibit re-colonization by grasses, leading to increasing bare soil (Brock et al., 2014). When rain returns, patches of bare soil induced by shrub removal create new opportunities for woody shrubs to re-generate.

Considering the above explanation, a relatively lasting effect of mechanical shrub removal on herbaceous properties compared to fire or herbicide was therefore intriguing. Due to low sample numbers of long-term data, we inclined to explain it based on specific landscape conditions. Some resulted from previously seeded plots (Redmon et al., 2013) or from invasive annual grasses rather than the expected perennial grasses (Bates et al., 2017). Long-term exclusion from grazing (Bates, 2005; Pierson et al., 2007), in addition to low shrub cover and density before treatment (Bates et al., 2017), is also thought to contribute to the lasting effect on herbaceous productivity after mechanical shrub removal (Fig. 2b). In addition, the presence of coarse woody debris which traps nutrients and provides a prolonged nutrient supply via decomposition (Daryanto et al., 2012) could also contribute to a relatively lasting effect of mechanical shrub removal on herbaceous productivity.

Another factor that potentially affects the trajectory of forage provisioning service is grazing itself. Expected increase in stocking rate with increasing rainfall (up to ~800 mm) could exacerbate herbaceous recovery after shrub removal (Fig. S1 in Appendix 3 of Supporting Information). This trend is consistent with a recent model by Yu and D'Odorico (2015) who suggest that shrubs, but not grasses, are favored in a more humid environment. As grass-shrub co-existence is also determined by the vertical distribution of water in the soil profile (i.e., grasses are favored by available soil moisture in the shallow soil due to their shallow root architecture), increasing rainfall allows more water to infiltrate to the deeper soils where shrubs have greater access to water (Yu and D'Odorico 2015). Although differences in root architecture also generate hydraulic lift that may benefit grasses (Yu and D'Odorico 2015), grazing reduces grass standing crop and therefore competition with shrub seedlings. Consequently, shrub's ability to recover following removal increases with increasing rainfall gradients (Fig. S2 Appendix 3 of Supporting Information), further generates negative feedback to long-term forage provisioning service.

Possible soil-related ecosystem service trade-offs that could be associated with shrub removal

Although our synthesis showed that both mechanical and fire treatment generate no changes with regards to upper layer SOC compared to the untreated control (Fig. 4), our understanding on C sequestration service and greenhouse gas (GHG) mitigation remained far from clear. To our knowledge, there has not been any studies that calculated ecosystem C and/or N budget following shrub removal. Various mechanical shrub removal methods generated different degrees of soil disturbance and oxidation of the previously protected aggregates. Treatments such as cutting probably generates no changes in SOC compared to ploughing which reduces SOC (Daryanto et al., 2013). Meanwhile, similar SOC level between burnt and unburnt treatments suggested that only low to moderate intensity fire was used in most fire experiments because the temperature was not high enough to cause organic matter oxidation (Fonseca et al., 2017; Zheng et al., 2016). Low intensity fire, however, increases soil-water repellency (hydrophobicity) (Zheng et al., 2016) and leads to high soil erodibility with decreasing inter-particle wet-binding forces.

Decreasing soil erosion control service could be immediate with fire management as bare soil increased and litter cover decreased (Fig. 4a). Erosion control service can be further suppressed by the loss of BCC (Canton et al., 2014) as it has been known to be susceptible to fire and very sensitive to disturbance such as trampling (Ferrenberg et al., 2015). BCC also has slow recovery (Fig. 4), particularly in the more arid shrublands (Evans & Johansen, 1999). Because OC is strongly retained by BCC's structure (Canton et al., 2014) and both are important to nutrient cycling in the drylands (Maestre et al., 2011), reductions in erosion control, C sequestration and nutrient cycling service provisioning could be among the most prominent trade-offs to the forage provisioning service following fire.

The same trade-offs likely occurred following mechanical shrub removal, although they may be delayed as the presence of litter and coarse woody debris reduced the cover of bare soil (Fig. 4b). However, mechanical shrub removal did not prevent BCC from destruction nor allow rapid recovery (Fig. 4b). Unless the mineralized nutrients resulting from shrub debris are recycled, the longer term soil nutrient status is lowered. Bare soil also returned similar to untreated control after decomposition of litter from shrub debris (Fig. 4b), generating reduction in nutrient cycling, C sequestration and erosion control service (Daryanto and Eldridge, 2010; Daryanto et al., 2013).

Our discussion on the effects of shrub removal using herbicide was greatly limited by data availability. In most cases, reduction in erosion control service with increasing bare soil and runoff would be expected to reduce infiltration in the longer term (Brock et al., 2014; Perkins & McDaniel, 2005), which in turn could generate adverse impacts on water cycling and services related to hydrology. This premise is supported by the recent findings of Wilcox et al. (2017) who show that increasing water supply service with shrub removal rarely occurs, except in winter rainfall areas where mean annual precipitation exceeds 500 mm, and with deep, permeable sandy soils. Although chemical shrub removal can be considered a less severe attempt to control shrubs compared to mechanical shrub removal due to the absence of physical soil disturbance, toxicity of residual herbicide (i.e., atrazine) particularly in bare soils that remained even up to eight years after herbicide application should be a concern. Dryland soils are characterized by low organic matter that inhibit microbial detoxification

(Hunter et al., 1978); a much higher rate of herbicide use to kill shrubs compared to other weeds in croplands often exacerbates this condition. In addition, under extreme dry condition, the application of herbicides (i.e., tebuthiuron) brings unintended consequences: a reduction in the herbage production (Britton & Sneva, 1981) and forage provisioning service.

Towards sustainable shrubland management

Our findings showed that shrub removal managed to achieve its objective only when a single ecosystem service (i.e., forage provisioning) is considered (Fig. 2). However, when other ecosystem services are considered, effect on the ecosystem may be negative as there are multiple soil-related trade-offs following shrub removal (e.g., erosion control, nutrient cycling). The option of subsequent shrub removal to maintain forage provision also requires careful consideration as trade-offs may be greater. For example, we note a reduction in SOC with multiple shrub removal (Fig. S3 in Appendix 3 of Supporting Information) as opposed to no change with one-time fire treatment or mechanical shrub removal (Fig. 4). Similarly, a decrease in litter cover was observed with multiple shrub removal (Fig. S3 in Appendix 3 of Supporting Information) instead of the short-term increase with one-time mechanical shrub removal (Fig. 4). Soil nutrients also decreased with multiple treatments (Fig. S3 in Appendix 3 of Supporting Information) while one-time mechanical shrub removal or fire still allowed short-term increase (Fig. 4).

Because management can alter not only the targeted processes, but also the non-targeted processes (Zhao et al., 2018), constant monitoring using methods that can be used by pastoralists is a key for adaptive management to detect early changes in landscape condition (Reed & Dougill, 2010). Management interventions such as fire may lead to the increase in obligate post-fire seeders (Shryock et al., 2015) and/or exotic species or annual species invasion (Goergen & Chambers, 2009; Miller et al., 2014; Steers & Allen, 2010), including possible emergence of vegetation- and resource-poor scabland with decreasing soil fertility, but increasing bare soil cover and soil erosion (Yu et al., 2016). In addition, sustainable forage production should focus on strategies to maintain multiple ecosystem services. These may include, but are not limited to, determining the appropriate stocking rate, applying rotational grazing, fertilizer and native perennial grass seeding because consideration of multiple services is expected to provide more effective long-term protection of the landscape and a broader range of environmental benefits.

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Conflict of interest statement

The authors declare that there is no conflict of interest.

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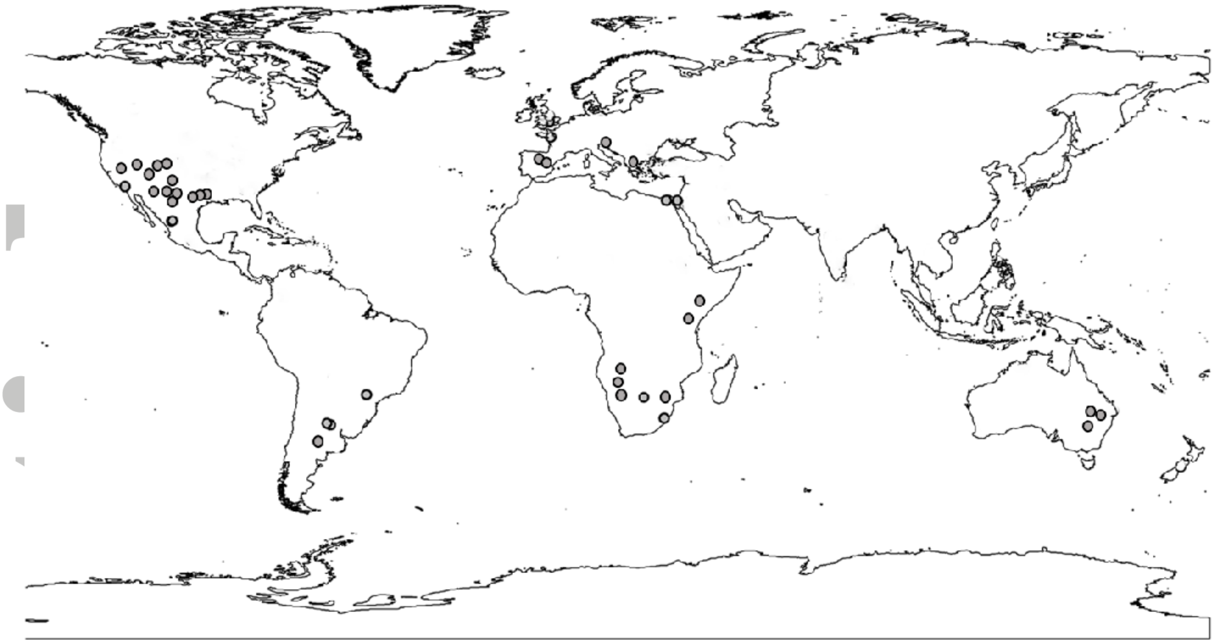

Fig. 1. Distribution of the study locations.

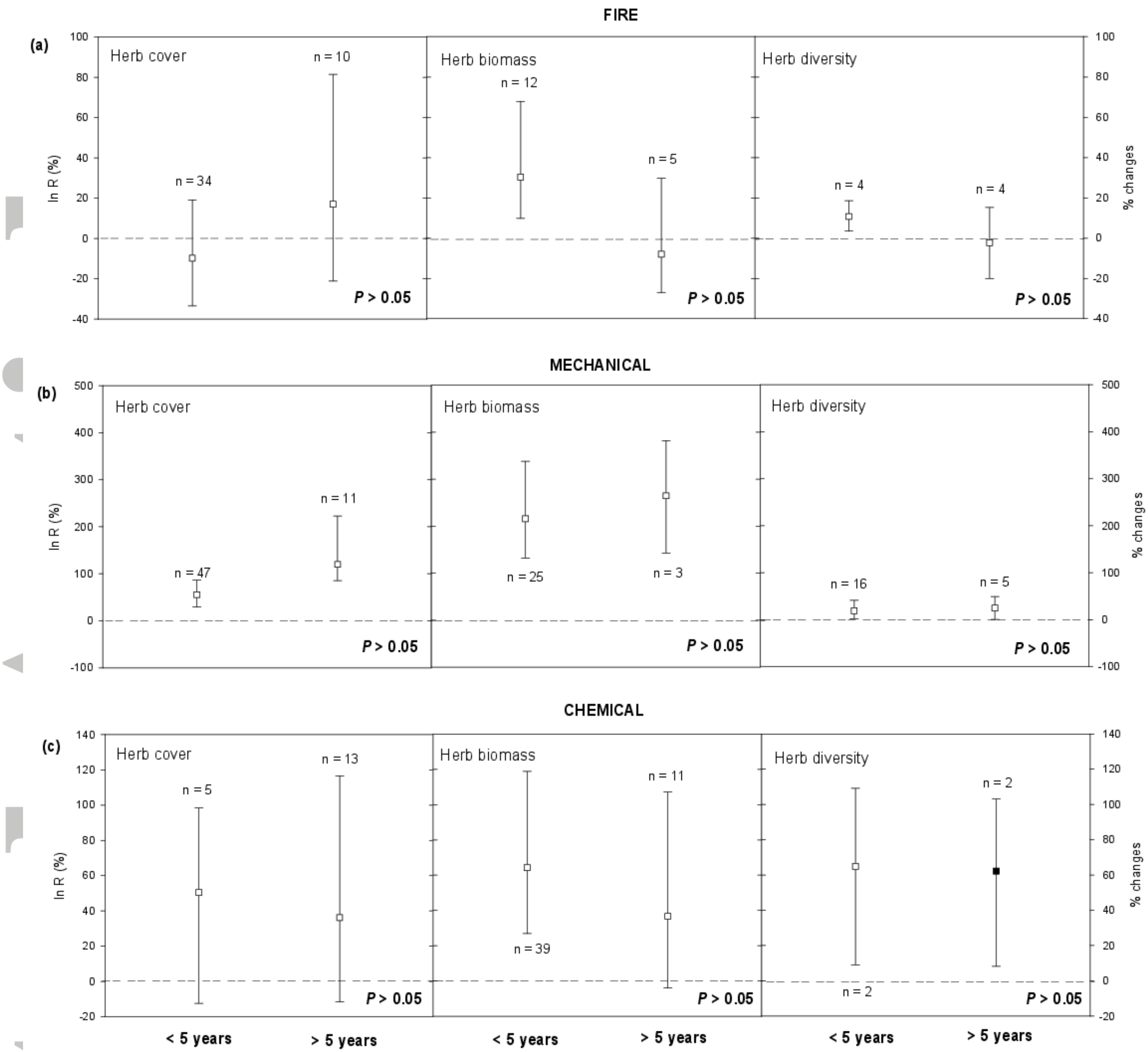

Fig. 2. Changes in herbaceous cover, biomass and diversity following fire (a), mechanical (b) and chemical shrub removal (c). Black dots represent the mean of *lnR* with error bar representing the 95% confidence interval (CI). A negative value indicates a reduction due to shrub removal treatment in comparison to untreated control which is only statistically significant when the confidence interval does not overlap zero. Letter 'n' indicates the number of samples. The *P* values indicate the statistical difference between categorical variables. Note differences in y-axis value.

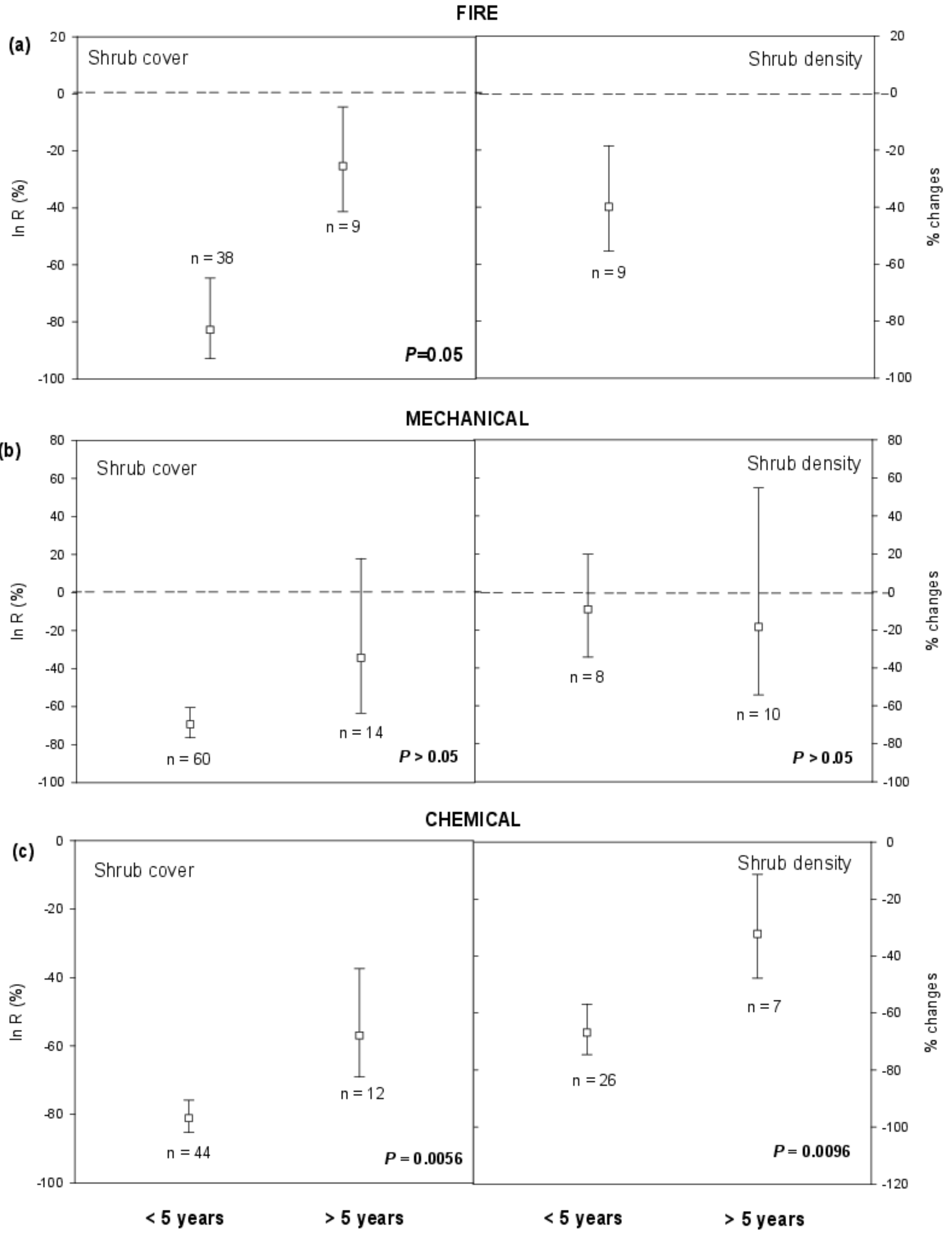

Fig. 3. Changes in shrub cover and density following fire (a), mechanical (b) and chemical shrub removal (c). Black dots represent the mean of *lnR* with error bar representing the 95% confidence interval (CI). A negative value indicates a reduction due to shrub removal treatment in comparison to untreated control which is only statistically significant when the confidence interval does not overlap zero. Letter 'n' indicates the number of samples. The *P* values indicate the statistical difference between categorical variables. Note differences in y-axis value.

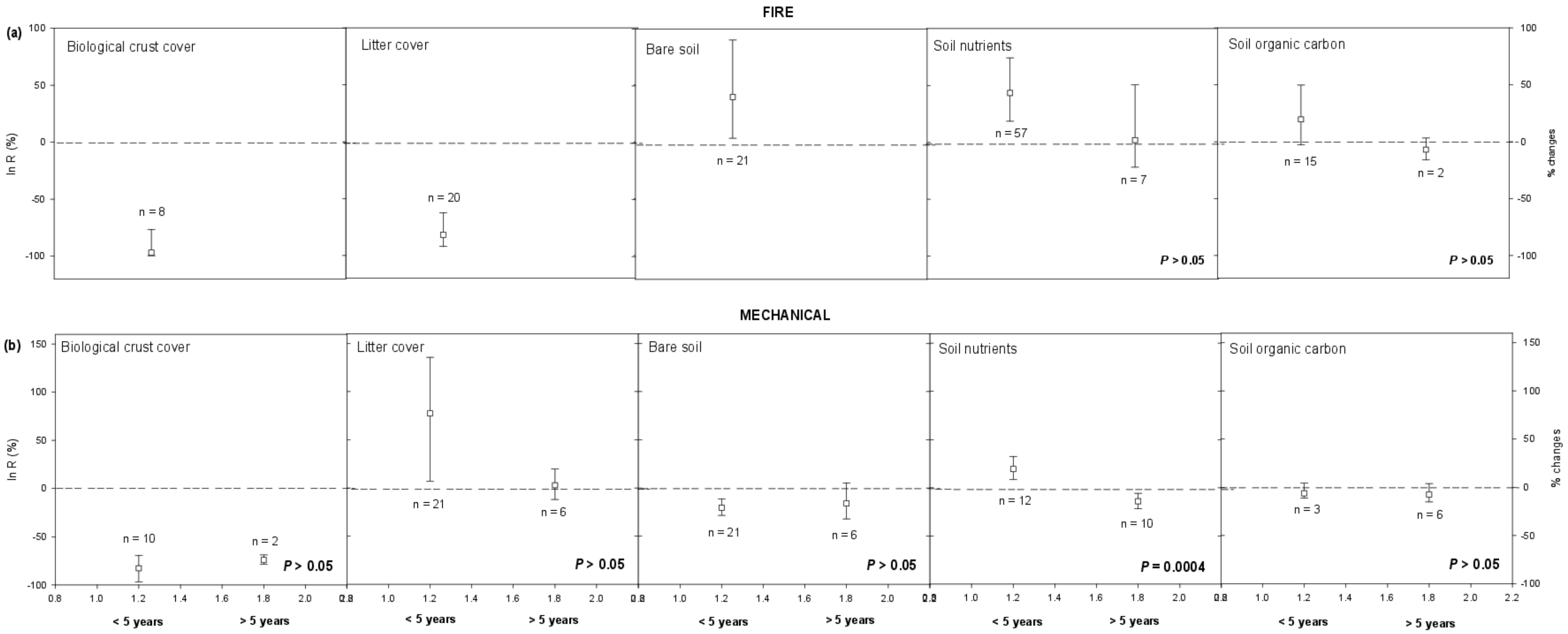

Fig. 4. Changes in landscape and soil properties following fire (a) and mechanical shrub removal (b). Black dots represent the mean of *lnR* with error bar representing the 95% confidence interval (CI). A negative value indicates a reduction due to shrub removal treatment in comparison to untreated control which is only statistically significant when the confidence interval does not overlap zero. Letter ‘n’ indicates the number of samples. The *P* values indicate the statistical difference between categorical variables. Note differences in y-axis value.